INFORMED CONTROL OF DOMESTIC ENERGY SYSTEMS

by

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Abstract

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The regulatory and economic pressures from climate change are driving adoption at the domestic scale of low and zero carbon microgenerators such as thermal and photovoltaic solar panels and combined heat and power units. For efficiency household energy use should be co-ordinated with the operation of these devices, but many consumers have difficulty controlling current heating systems so are unlikely to be able to provide the management interventions needed. A control system is required that can collectively optimise a diverse range of energy sources and sinks on behalf of the consumer while providing them with useful information. This system should also respond to the dynamics of grid electricity, for example the variability of output from large scale wind generation, so that embedded microgenerators contribute to the matching of electricity supply and demand. Its realization is the focus of this work.

A hypothesis is proposed that ecosystems, which seek and conserve exergy through complexity and diversity of species, offer a model for this control system and the complex range of devices it must manage. To test it, the performance in actual domestic use of several microgenerators is investigated and opportunities for collective optimisation are identified. Minimisation of exergy loss is shown by analysis and computer modelling to be preferable as an objective function when compared to minimisation of carbon emissions or cost, and capable of effective use as a signal for management of electricity demand and despatch of micro generators. To facilitate complexity and diversity, techniques are devised to automatically identify and characterise microgenerators, other appliances, the thermal properties of a home, and consumer energy needs.

A prototype control system providing many of these functions is designed, implemented, and tested. It is shown to be capable of improving the energy efficiency of many households, and increased comfort for certain disadvantaged consumers. A conclusion is offered that exergy loss is preferable to market price as a system management metric for all aspects of renewable energy capture, distribution, and use.

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Abbreviations

BETTA	British Electricity Trading and Transmission Arrangements
BSI	British Standards Institute
CCGT	Combined Cycle Gas Turbine
CERT	Carbon Emissions Reduction Target
CHP	Combined Heat and Power
CIBSE	Chartered Institute of Building Services Engineers
CSV	Comma Separated Variable
DCLG	Department of Communities and Local Government
DEFRA	Department of Environment, Food, and Rural Affairs
DGCG	Distributed Generation Co-ordinating Group
DNO	Distribution Network Operator
DTI	Department of Trade and Industry
ENA	Electricity Networks Association
ENSG	Energy Networks Strategy Group
ERA	Energy Retail Association
EU	European Union
GSP	Grid Supply Point
HAN	Home Area Network
ISO	International Standards Organisation
LZCT	Low and Zero Carbon Technology
MPAN	Metering Point Administration Number
ODPM	Office of the Deputy Prime Minister
OPSI	Office of Public Sector Information
PMV	Predicted Mean Vote
PV	Photovoltaic
ROC	Renewable Obligation Certificate
WAN	Wide Area Network

Nomenclature

a,b,c,d	Half-hour intervals from the diurnal cycle in which heating start (a,c) and stop (b,d) events occur	time instant
C_h	Thermal capacity of house	kWh/ °C
C_r	Thermal capacity of radiator circuit	kWh/ °C
E, E_L	Exergy, exergy loss	kWh
F	Flow rate	ml/s
H, H_c, H_i, H_o, H_s	Heat power (from micro CHP, in ith half-hour interval, from occupants, from sun)	kW
K	Calorific value of fuel per unit of volume	J/m^3
L_i	Proportion of exergy lost in ith half-hour interval	ratio
O	Occupancy	no. of people
$P(A\|S)$	Probability of A given S	ratio
P_e	Mean electrical load over a time step	kW
P_i	Mean electrical power consumed or generated in ith half-hour interval	kW
P_o, P_d, P_m	Instantaneous electrical power (from generator, to load, from import)	kW
Q	Thermal energy	kWh
T, T_s, T_e, T_r	Temperature, (set point, external, room)	°C
T_c, T_h	Temperature (of water on cold side and hot side of a solar hot water panel)	°C
T_{cm}	Temperature for comfort (PMV is neutral)	°C
T_f, T_t, T_b	Temperature (feed to hot water tank, upper volume of hot water tank, lower volume of hot water tank)	°C
T_{rm}, T_{re}, T_{ri}	Predicted room temperature (morning, evening, ith half-hour interval)	°C
T_{em}, T_{ee}, T_{ei}	Predicted external temperature (morning, evening, ith half-hour interval)	°C
T_o	Temperature of surroundings or environment	K

T_{out}	Temperature outdoors in context of PMV	°C
T_{ws} , T_{rs}	Temperature (water return and room at the time heating stopped)	°C
t, t_i, t_m, t_e	Duration of energy input (during ith time step, duration of morning and evening heating sessions)	elapsed time
V, V_b, V_t, V_d	Volume (of hot water tank below heated volume, heated volume, draw off volume)	litres
W, W_h	Heat loss rate per unit of temperature difference (of house between interior and exterior)	W/ °C
η, η_e, η_h	Efficiency (electrical and thermal efficiency of CHP unit)	ratio

1 INTRODUCTION

1.1 Overall Aims and Hypothesis

Since prehistory the inhabitants of the British Isles have needed sources of energy to provide heat and light in their homes through the winter months and at least part of the spring and autumn seasons. The ready availability of coal, and the temperate nature of winters in these isles, led during the industrial era to house construction methods, and methods of fuel combustion, that are not very efficient by comparison with those used in continental countries. However, rising levels of carbon dioxide in the atmosphere and compelling evidence of the consequent climate change have motivated Government policies intended to reduce the profligate use of, and dependence on, hydrocarbon fuels. These policies are summarised in the Energy White Paper (DTI, 2007), and in association with economic pressures from rising hydrocarbon fuel costs, are encouraging development of energy efficiency measures and renewable energy sources.

This research seeks to contribute towards more efficient and less carbon intensive use of energy in the domestic environment by showing how more information can be made available to the processes that control and manage energy conversion devices in the home. The aims of the research will first be described, and a radical hypothesis, to be tested in theoretical and experimental investigations, will then be proposed concerning methods of control optimisation.

The drive for lower carbon emissions is leading to a number of revolutionary changes in the electricity industry. One of these is the adoption of renewable energy sources such as wind, sun, and wave powered generators. Because these energy sources are inherently more diffuse than stored hydrocarbons, the individual generators tend to have a much lower output than fossil fuel power stations and hence must be far more numerous. Solar photovoltaic (PV) and micro-wind generators are now available at a scale which is practical for many dwellings. However, if such generators are to be deployed in the scale of millions as Government policy intends, then for reasons of security of supply, safety, and economics, they must be managed as part of the national electricity generation resource. This implies there must be an exchange of information between the generator (or the person operating it) and the systems managing the national grid and local distribution networks. This leads to the first aim of the research:

to devise an optimum technique by which large numbers of domestic scale generators can be economically controlled, metered, and monitored.

The second aim follows from the increasing complexity and diversity of energy conversion devices that can be expected in the home, as micro combined heat and power (micro CHP) units replace gas boilers, air conditioning becomes necessary through climate change, and solar water heaters, wind turbines, and PV generators become commonplace:

to demonstrate a method for collective optimisation of domestic energy conversion and consuming devices.

The final aim is to further exploit the information technology needed for the first two aims:

to improve the information on, and control of, energy use available to the consumer.

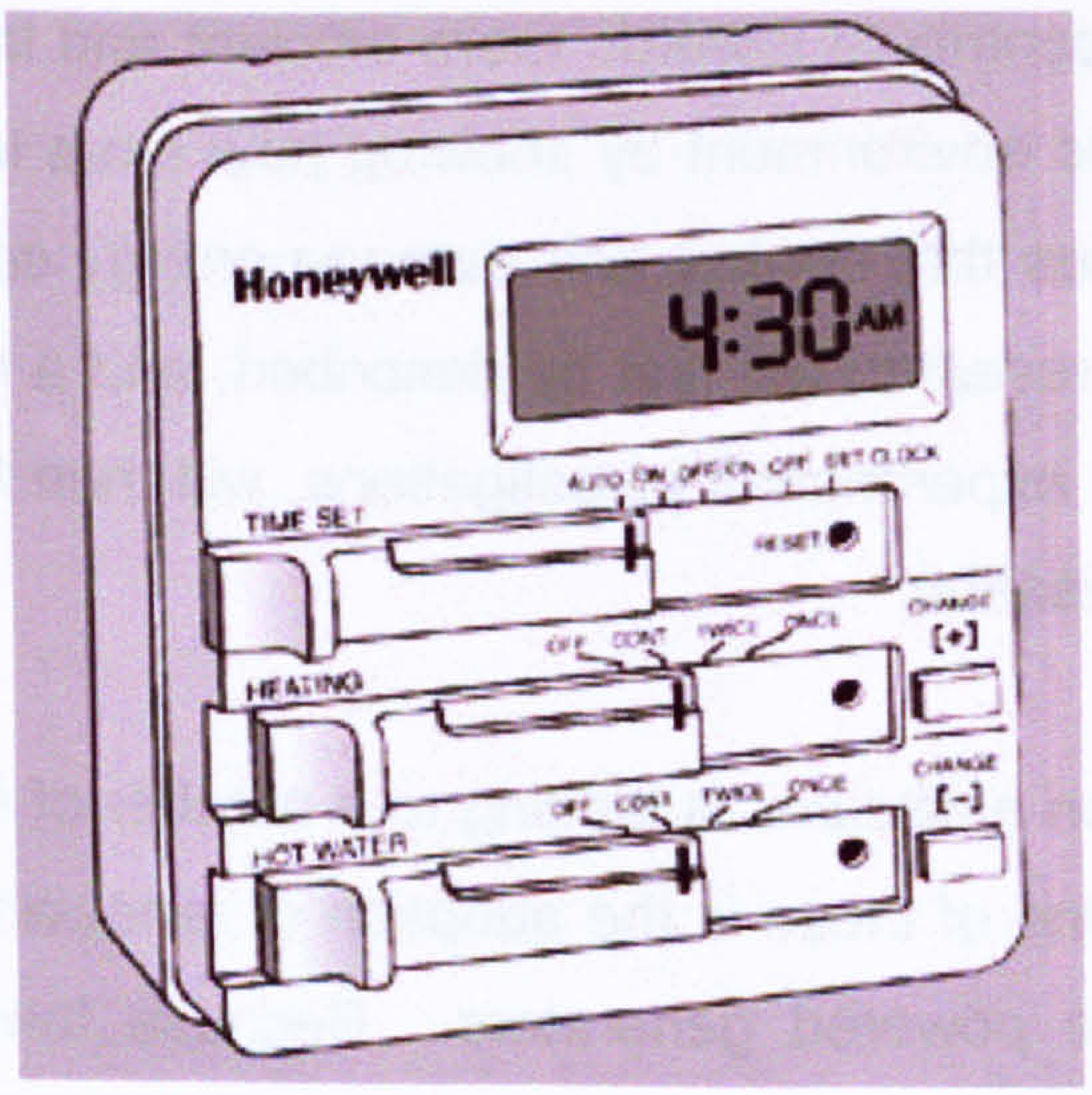

Figure 1-1 Example little white box (Honeywell 2007)

At present, in most homes there are one or more little white boxes such as that shown in Figure 1-1. Alternatively small grey control panels may be observed on heating appliances, while an electricity meter can be found in a dark corner of every home. These little boxes each perform, in isolation, limited control or monitoring functions for a subset of the energy conversion devices in the dwelling. The aims set out above are headline requirements for an advanced family of little white boxes that interact with the outside world and each other, take account of all the energy conversion devices in the home, and have a sophisticated human interface that does not demand unrealistic amounts of attention and provides useful information. Because of the diverse nature of the buildings, people, appliances, and climatic conditions these devices will have to deal with, it would greatly simplify the engineering problem if a unifying theme or model can be defined that can provide a basis for their design and the control decisions they take.

This thesis argues that such a unifying model does exist - it is the way energy flows through a natural ecosystem. By making the energy-using or -generating artefacts around him behave in certain ways more like living things, the symbiosis between man, his created environment, and the natural world, can be improved. Clearly the arrival at a domestic scale of technologies such as PV, which capture solar energy and so perform a plant-like function, opens up a richer range of possible resemblances between an artificial system and a natural ecology. So the hypothesis proposed is that:

> *the efficiency of domestic energy conversion and consumption is optimised by convergence towards the non-equilibrium thermodynamics of living organisms.*

Some practical properties consistent with this hypothesis are that a control system created in accordance with the model of a natural ecology should:

- minimise consumption of exergy (as further defined and discussed below);
- ensure energy is captured, stored, and consumed in a cyclic manner synchronised with the behaviour patterns and needs of the household occupants;
- cause the domestic energy system to operate as a partly closed system exchanging energy in a controlled and mutually sustaining way with a nested set of larger systems, of which it is a component;
- since human artefacts cannot yet reproduce themselves, it must justify the cost of its own manufacture and use so that it becomes widely adopted on its economic merits.

The assembly of evidence to support this hypothesis, and of engineering requirements that derive from it, begins with basic physics and published research concerning the energy use of ecosystems, to show that a usable unifying model exists. Observations are gathered, both from the literature and from direct experiment, which prove that opportunities exist for a control system to beneficially manage energy converting and consuming devices in the manner proposed. Results of computer modelling are presented which extrapolate the experimental results to a range of domestic scenarios and national scale implementations. An evaluation of the hypothesis is then performed by comparing, on paper, the control optimisation model derived from ecosystems with one that is driven by current energy market economics, and a model that takes control decisions based on minimisation of carbon emissions. The feasibility of the proposed control system is then investigated by setting out in detail the functions it must perform, and practical techniques which could implement them. Finally an experimental realisation of the control system, and the results obtained from it, are described.

The aims and hypothesis lead to quite a broad context for the research with the following main topics:

- The physical, ecological, and economic manifestations of non-equilibrium thermodynamics.
- Government policy relating to domestic energy use, and its direct consequences such as the operation of the electricity market.
- Small scale renewable energy and microgeneration technologies and their impact on electricity distribution networks.
- The human factors around energy use in the home.
- The literature directly relating to domestic or community energy management.

The next chapter reviews the literature on each of these topics, picking out current directions and promising ideas that are carried forward in this work. It also details the arguments leading from the hypothesis to the practical properties of a control system implementing it. Chapter 3 describes the test bed comprising micro CHP unit, PV panels, and solar water heater, which has been used for practical investigation and demonstrations. Chapter 4 begins by conducting the evaluation of the hypothesis as described above, and then uses the literature survey and the results of practical experiments and modelling to identify key functions and capabilities which a domestic energy control system should provide to meet the aims of the thesis. Chapter 5 sets out a concept for realisation of the "advanced little white box", discusses implementation options, describes the prototype that was constructed, and presents the results from use of the prototype. Finally Chapter 6 evaluates the extent to which the aims have been satisfied and the thesis validated, then summarises the knowledge gained from the entire project and the scope for further work.

This overall approach is influenced by the first of four principles for researchers seeking to support environmental sustainability, as propounded by Clark (2003) in an inaugural address to a new institute[1] (reported by Houghton, 2004):

[1] The Zuckerman Institute for Connective Environmental Research, University of East Anglia.

"Research should have a goal of finding solutions not just characterising problems. There is a tendency among scientists to talk forever about problems but leave solutions to others. Applied research seeking solutions is just as challenging and worthy as so-called fundamental research identifying and describing the problems".

2 ENERGY IN THE HOME – PHYSICS, POLICY AND RESEARCH

2.1 Structure

The literature review presented in this chapter begins with the background provided by the underlying science and Government policy. The particular issues of distributed electricity generation are then examined, which are a combination of physical, engineering, and regulatory factors. Finally the main antecedents of the present research are reviewed, and gaps are identified which could be filled by this work. Throughout the chapter requirements are identified that must be satisfied by the "advanced family of little white boxes" as conceived in the Introduction. These requirements are drawn together and developed in Chapter 4.

2.2 Thermodynamics of Sustainability

The conventional method for determining energy efficiency is based on the First Law of Thermodynamics, which states that energy is conserved during transformation between its various forms such as potential, chemical, kinetic, electrical, and heat energy. The efficiency of an energy conversion device may therefore be calculated as the energy contained in the useful output of the device divided by the energy input. This information is valuable for many purposes but does not take into account the "quality" of the energy inputs and outputs. For example, 1kWh of electrical energy from a photovoltaic roof panel can be used to power a computer, or an electric motor, or heat water, etc., whereas 1kWh from a thermal solar roof panel can be used for little other than domestic hot water heating and space heating.

This difference in quality arises from the Second Law of Thermodynamics, which states that not all the energy input to a system can be converted into useful work, and allows the amount of work obtainable to be determined for a given system. In this context a system comprises the energy source, the energy conversion device and the environment to which the "waste" energy is discharged. Exergy (also known as availability) is the thermodynamic metric which quantifies the potential of an energy source within a given system to deliver useful work, and exergy efficiency expresses the extent to which that work is extracted from the source.

This approach to the analysis of energy flows has given insights into the behaviour of ecological systems. A robust strand of investigation has been established on the boundary between biology and physics concerning the role of thermodynamics in shaping ecosystems and the evolution of species. The central thesis of this work by Schneider and Sagan (2005), Kay (2000), Ulanowicz (2006), and Ho (2005), and others, begins with the observation that if an energy gradient is imposed on inanimate matter with suitable temperature and phase conditions, structures emerge spontaneously from initially chaotic conditions. These structures have the effect of increasing the local rate at which energy flows across the gradient. Hurricanes, and Bénard cells which appear when a fluid in a flat dish is heated as shown in Figure 2-1, are classic examples of this phenomenon.

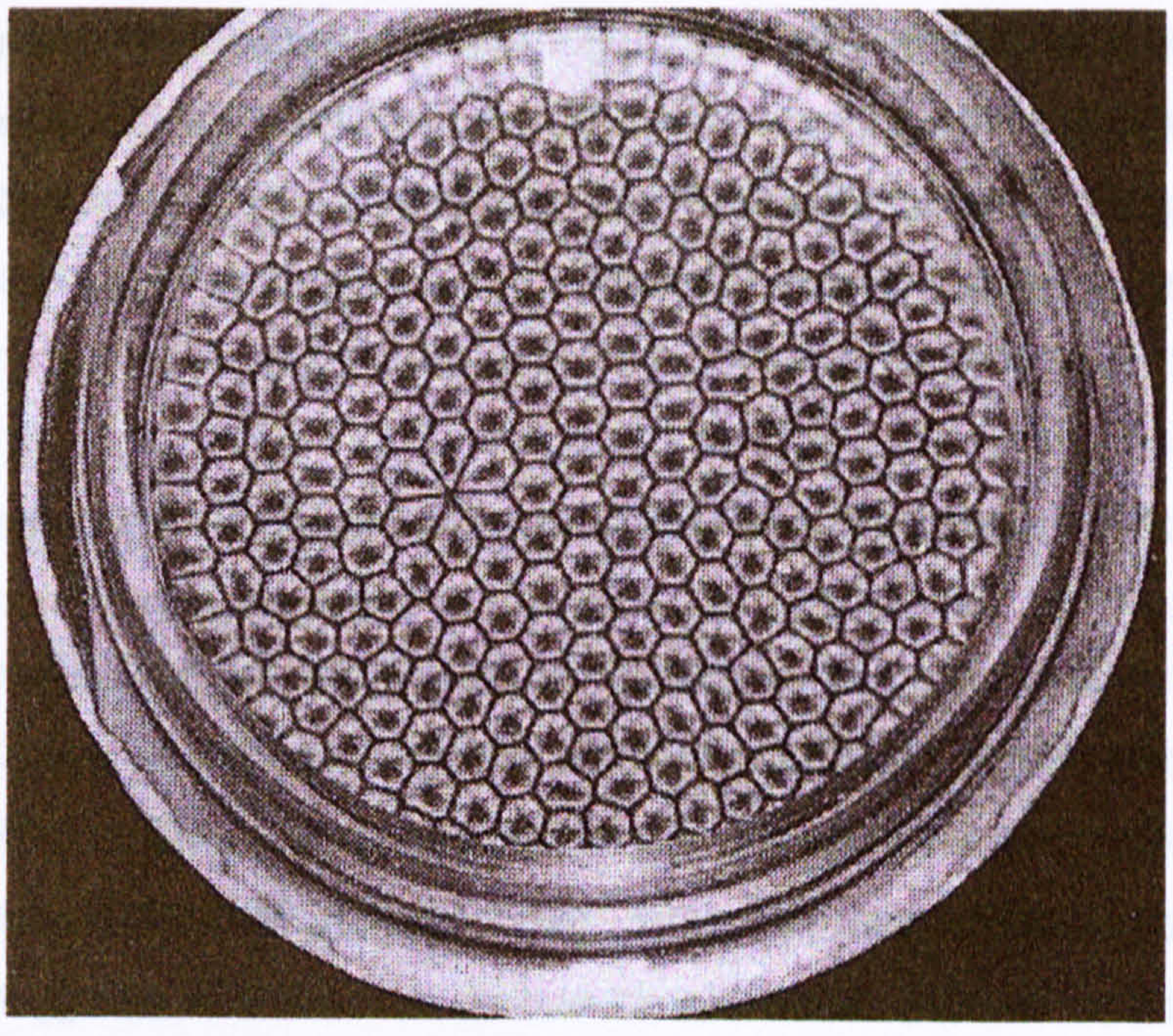

Figure 2-1 Bénard cells (from Koschmieder 1991)

Their research demonstrates that similar non-equilibrium thermodynamic processes are a strong motivating factor in the development of complex ecosystems, which are more effective in the dissipation of the sun's radiation than simple ecosystems, and that efficient energy capture and use is a key factor in the selection of species. An example of the experimental evidence for this is Luvall and Holbo (1989), who used an aircraft-mounted infrared scanner to collect data on the thermal emissions from different landscapes and showed that when other parameters were equalised the temperature of radiated energy from the ground was dependent on the ecological richness of the surface vegetation, and lowest for mature forest.

This line of argument leads to the conclusion that there is a continuum of such emergent structures, of increasing complexity and efficiency in finding and consuming energy. These structures begin with simple physical phenomena such as water rotating when the bathplug is withdrawn, and extend through chemical autocatalytic cycles, such as the Belousov-Zhabotinsky reaction (Nicolis & Prigogyne, 1989), into all the manifestations of life, and ultimately emerge as human economics driven by dissipation of fossil fuels, in which organisations at various scales compete for dominance in the production of goods and services. The proposition that all economic activity is directly driven by thermodynamic laws is controversial; some authors such as Hammond (2007) consider economic and thermodynamic systems to be merely analogous. However, those human artefacts and economic activities that are directly concerned with the acquisition and exploitation of energy are unavoidably governed by the physics of energy. There is also an argument that all genuinely sustainable economic activity must reflect the underlying non-equilibrium thermodynamics (Bey and Isenmann, 2005). This thesis, in making the case for ecosystems as a practical model for sustainable domestic energy systems, supports their macroeconomic argument with a microeconomic example.

The term dissipation, although widely used in the literature to express the effect of emergent structure, is somewhat misleading as it suggests conversion of the energy gradient to low grade heat. A more consistent model is provided by viewing the emergent structure, such as a hurricane, as a self contained system which seeks to intercept and consume the energy flowing in the gradient external to itself. Some part of the external energy that is drawn into the system suffers an increase in entropy, but a significant proportion is likely to be stored and as a result the exergy in the source is partly conserved. In the case of the hurricane this is as the kinetic energy of the rotating air mass. In the case of plants, exergy storage is in the form of the chemical structure of the growing plant, while the increase in entropy arises from the transpiration processes that draw liquid water through the plant and convert it to water vapour. In both cases it is the stored exergy that provides the visible manifestation of the emergent structure. The balance between exergy storage and exergy degradation through increasing entropy will tend to stabilise at the point which best achieves consumption of the energy gradient. For ecosystems, the proportion of stored exergy increases as the system evolves and becomes more complex, and exergy conservation becomes the primary goal of the system (Ulanowicz, 2006).

However, it is important to note that the scope and extent of these emergent structures, and hence their ability to consume an energy gradient, is limited by a variety of boundary conditions. In the case of the hurricane these conditions include the height of the atmosphere, the sea temperature, and the Coriolis force generated by the earth's rotation. These limit its size and intensity at a given location. For the ecosystem, the key constraint, apart from the local conditions determined by climate and geography, is the available genetic diversity. This can grow very slowly over time, but typically a given ecosystem will reach a "climax" which represents its maximum capability to absorb the solar energy gradient. This climax is most often bounded by the limit in the aggregate genetic information present across all the species in the ecosystem and the rate at which evolution can take place from that gene pool, not by the physical constraints of the environment.

There are four important implications for the design of domestic energy systems from this analysis of the natural world. The first and most obvious is that if human beings cannot go on consuming the energy gradients provided by fossil fuels they must sustain themselves as emergent systems by finding better ways of recognising and consuming solar energy gradients (or gradients within emergent phenomena such as wind and waves that have themselves captured solar energy), at least until a universally acceptable and economic method of access to nuclear energy is found.

Secondly, the lesson from the high exergy efficiency of the rain forest is that the route to greater efficiency in the capture and use of solar energy is through greater complexity and diversity in the methods used for the purpose. The equivalent of genetic information in human artefacts is the information necessary to create the variety and complexity of the designs, the range of scales in time and space on which they operate, and the sophistication of the economic value chain which brings them into existence.

Thirdly, the man-made systems created to exploit the solar gradient need to be able to extend as far as possible their physical and information limits so that their "climax" form is as capable as possible. Now on a crowded island such as the UK, with a mature and complex society, physical limits can be rapidly reached and be very difficult to overcome. The "not in my back yard" constraints on wind farms are already a serious limit to expansion of capacity on land. Diversity of scale alone is helpful – many small wind turbines may be acceptable where a large wind farm is not. But information limits are far from being reached – the information technology currently being applied in the energy industry is primitive compared to the telecoms industry which has in many ways a similar utility relationship with the consumer. There should therefore be real scope for improving energy capture and use within given physical limits by introducing additional complexity.

Finally, the goal which drives the decision taking of these information systems should be exergy capture and conservation, because that is what drives the maturation and success of an ecosystem. Much ingenuity has already gone into solar exergy capture, evident from the variety of devices available. Building standards and public information campaigns also rightly emphasise thermal insulation, which provides the final barrier before total loss of exergy content in domestic energy flows. But the ecosystem model shows that between capture and total loss there should be many steps of controlled exergy storage and degradation operating on a variety of timescales. These require a lot of information to build and operate, and are largely missing from current man-made energy systems, which simply assume that an energy source with high exergy content is always available either from mains electricity or from fossil fuels.

These four implications provide a practical interpretation of the hypothesis, which can be framed as four technical requirements for the proposed control system:

- It must recognise a solar energy gradient (e.g. a PV panel) and encourage its human owners to find more (e.g. by maximising the return they obtain on their investment).
- It should facilitate complexity and diversity in domestic energy devices by being able to operate with as wide a range of devices as possible.
- It should extend information limits, which the literature discussed later in this section shows are currently bounded by the consumer's attention span and ability to comprehend, by hiding the complexity arising from the second requirement as far as possible and by presenting a convenient human interface.
- It should minimise exergy loss from the available energy flows and make maximum use of storage opportunities, such as in the thermal mass of the building.

These requirements are further developed in Chapter 4.

2.3 *Information and Entropy*

Another fundamental reason why information processing techniques should be relevant to energy systems arises from the deep relationship between information and entropy. Boltzmann's equation relates entropy to the number of possible microstates that the molecules of a volume of gas can occupy:

$$S = k \ln W$$

If any attempt is made to extract work from the volume of gas (for example by Maxwell's demon, who recognises fast molecules and captures them) resulting in an entropy reduction ∂S, then the corresponding ∂W represents the information that the demon would need to achieve this feat. However Brillouin (1962), Landauer (1961), and others have shown that because each bit of information costs an entropy increase of at least $k\ln 2$ to obtain (known as the Landauer limit), then the demon's activity cannot be self sustained.

This argument, while simply confirming the validity of the Second Law, implies that the entropy of a closed system at equilibrium cannot be reduced by the addition of information, so is not very encouraging to this thesis. However, a practical system differs from Boltzmann's volume of gas in two ways. Firstly it is not at equilibrium – we are interested in making more efficient use of external energy gradients provided by the sun or fossil fuels. Secondly, we are interested in embedding the acquisition and use of information *inside* the system – the problem of a system knowing its own microstate is different from an external observer knowing its microstate, though the minimum cost of information remains the same. For a system with a gradient to draw on, the cost from the Landauer limit can be offset by increased dissipation of the gradient. When Bénard cells emerge from the random motion of heated oil it is evident that there is a reduction in entropy within the system comprising the oil, due to the information that the oil itself has generated and employed in creating the cellular structure. This reduction is accompanied by increased consumption of the applied heat gradient, ensuring the Second Law is observed.

Unfortunately a general quantitative model of the processes leading to the formation of Bénard cells and similar non-equilibrium phenomena is not possible with the present state of knowledge because the precursor events – the random turbulence of the fluid - are chaotic. While the mathematics of chaos allows for the emergence of patterns, few simple predictive relationships are available.

The conclusion drawn here from the relationship between information and energy is that by increasing the information available within a man-made non-equilibrium system it should be possible to improve its acquisition and use of an external energy gradient. Landauer's limit shows that there is a minimum energy cost to that information. This is intuitively reasonable from everyday experience and lends support from basic physics to the ecological model developed above – if we can provide a system with information on where and when solar energy can be found, then it can make better use of it. In Chapters 4 and 5 a method for achieving this is described.

2.4 UK National Energy Policy

Any proposals for an energy management system that is to be widely used must take account of the political and economic climate in which it will have to operate. The central statement of current UK national energy policy is the aim of 60% reduction in carbon emissions by 2050, originally asserted in the 2003 Energy White Paper and reconfirmed in the 2007 update (DTI, 2007). To realise this aim, goals are set for 16% of UK electricity to be supplied by renewable sources by 2020, and carbon emissions from residential use of energy to be reduced by 35%. Previous policy papers have cited the means by which these goals might be achieved for the domestic sector, including take up of about 400,000 micro CHP units (DEFRA, 2004) and 200,000 photovoltaic installations (DTI, 2004). These numbers are aspirational rather than definitive since they depend primarily on market forces and progress towards them has so far been limited.

The two main policy measures from the 2007 White Paper directed at domestic carbon emissions are the Carbon Emissions Reduction Target (CERT) and a proposed change to building regulations requiring new homes to be "zero carbon" from 2016. CERT has now been promulgated in a Statutory Instrument (OPSI 2008). This puts an obligation on energy suppliers to assist their customers to save energy or change to less carbon intensive sources such that an annual reduction of 4.2M tonnes in CO_2 emissions is achieved by 2011. Suppliers are able to employ any technology to achieve their obligation that fits within four categories:

- achieving improvements in energy efficiency;
- increasing the amount of electricity generated or heat produced by microgeneration;
- increasing the amount of heat produced by any plant which relies wholly or mainly on wood;
- reducing energy consumption.

The potential for carbon savings from improved heating controls is recognised in the Statutory Instrument by the inclusion of 400,000 installations in the "illustrative mix" of measures cited in the document to demonstrate the feasibility of the target to suppliers.

The "zero carbon" requirement in building regulations from 2016 has now been published as a firm policy (DCLG 2007). It specifies that any use of fossil fuels or grid electricity by a housing development must be offset by low or zero carbon electricity exports from within the development. This is clearly going to promote extensive deployment of PV and small or micro scale CHP given the expected build rate in 2016 of 200,000 dwellings per year.

The other major national policy aim related to domestic energy use is to eradicate fuel poverty by 2010, as set out in the UK Fuel Poverty Strategy (DTI, 2001). Clearly innovations in domestic energy systems should address this aim as well as carbon mitigation. The main policy measure is a grant scheme for energy related home improvements called Warm Front - an opportunity for this research to assist the effectiveness of this scheme is discussed in 2.6.4.

2.5 Technical and Commercial Issues of Distributed Generation

The simultaneous deployment of centralised and "embedded" generation of electricity, such that generators can occur anywhere and at any voltage level in the UK electricity distribution network, leads to certain technical and economic issues which must be solved if security of supply is to be maintained and the totality of generation capacity is to be used in the most carbon- and cost-efficient manner. The electrical engineering community has for some time believed that as the level of aggregate capacity from these embedded generators rises it will be essential to integrate them with the rest of the national power generation and distribution system (Jenkins *et al*, 2000). This will require a set of suitable technical and commercial operational processes that deal with the main issues, which may be summarised as:

- Maintenance of power quality and safety.
- The variability of output from generators that are dependent on the weather (wind and PV) or heat demand (CHP).
- Quantifying the value of, and paying for, the output of small generators.

In 2001 the DTI and Ofgem (the energy industry regulatory body) initiated the Distributed Generation Co-ordinating Group (DGCG) with representatives from all stakeholders in the electricity industry to address these problems. The DGCG commissioned or produced a series of studies which have now reported, covering topics including:

- The effect of domestic generators on voltage stability (Ingram et al, 2003). This showed that there is a risk of overvoltage conditions occurring when the local penetration of domestic generators exceeds 45% of dwellings.
- The electrical and safety specification for connection of domestic CHP units to the mains supply (ENA, 2003).
- Quantifying the benefits of small generators to the power system and to the environment, and hence the economic value of their output (DGCG Technical Steering Group, 2004).
- Methods of metering and payment for the output from small generators (Ilex Energy Consulting, 2005a). This study shows the limitations of current metering technology, and also a lack of data on the amount of electricity that domestic generators will export to the grid. Both issues represent research gaps that are addressed in later chapters.

Following this initiative the development of design rules and installation practice to deal with power quality and safety is now reasonably mature. A Manchester estate of 500 houses has been equipped with micro CHP units, and initial results show no serious voltage or frequency stability problems (Beddoes *et al*, 2007), although operation is close to the edge of statutory parameters. Micro generator connection standards such as (ENA, 2003) are proving acceptably low cost to implement and reliable in practice despite stringent safety features.

Dealing with output variability is a much more challenging problem. The exhaustive analysis of wind generator statistics by Sinden (2007) shows that while the UK wind resource in total is far more reliable than a single wind farm, nevertheless there is substantial short term variability. Figure 2-2 shows the daily variability in UK wind power capacity factor (i.e the generated output expressed as a percentage of the rated peak output of the installed plant) averaged over 34 years.

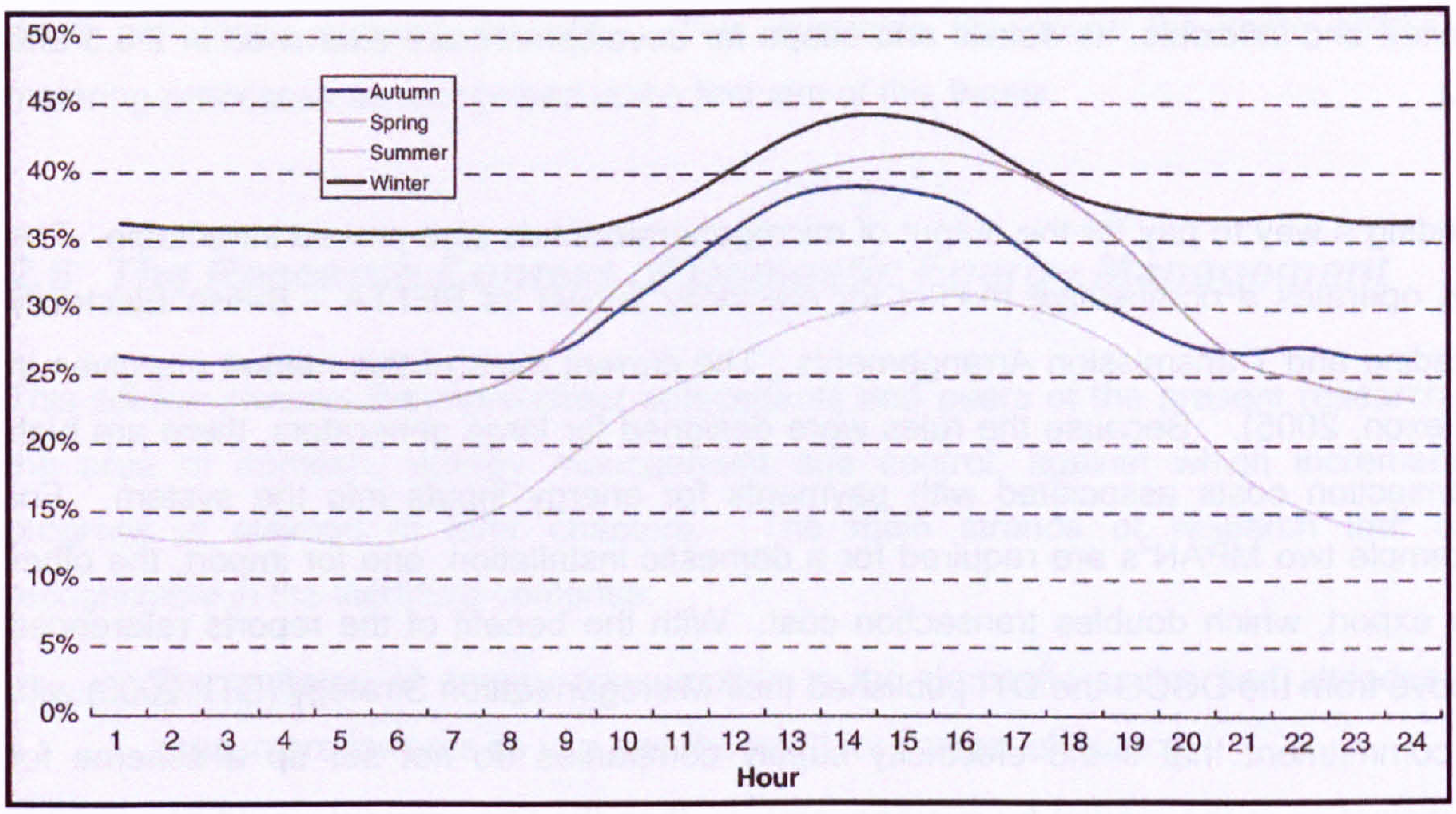

Figure 2-2 Average wind generator output power over 24 hours (from Sinden 2007)

It can be seen that taking the summer profile as an example wind output will frequently rise by 100% within 10 hours. This behaviour is quite predictable and in principle can be handled by balancing plant, using current technology this comprises coal and gas fired generators units whose output can be varied readily. The difficulty with this method of operation is that there is an engineering trade off between efficiency and flexibility in large scale generating plant. The older, less efficient plant can provide flexibility but at the cost of high carbon emissions. More modern and efficient plant such as Combined Cycle Gas Turbines (CCGTs) cannot be operated cost-effectively with variable output due to the reduced reliability caused by thermal stress (Boyle *et al*, 2007). Introduction of carbon capture will also force operators towards a stable running regime to maintain the efficiency of the chemical processes involved.

The obvious conclusion is that offsetting the variability of renewable generators cannot be left to balancing plant alone, there must be some effort to align demand with the availability of generator output. This approach, generally referred to as demand side management, becomes even more desirable when the proportion of generator capacity provided by renewable sources rises to the point that generator output can exceed demand. Unless demand can be directed to "soak up" such peaks, it will be necessary to shut down wind generators, with consequent loss of income to the operator. This effect is expected to begin to occur when wind is supplying about 20% of overall electricity demand (Sinden, 2007), so will act as a disincentive to further growth unless demand can be managed. A demand side management system for domestic consumers does exist in the UK based on the Economy 7 tariff scheme, but it is very limited and inflexible. Its details and scope for development are examined in 2.6.3 and 4.4.

Finding a way to pay for the output of microgenerators has also proved intractable. The UK operates a competitive market for electricity known as BETTA – British Electricity Trading and Transmission Arrangements. The current rules of this market are given in (Elexon, 2005). Because the rules were designed for large generators, there are high transaction costs associated with payments for energy inputs into the system. For example two MPAN[2]s are required for a domestic installation, one for import, the other for export, which doubles transaction cost. With the benefit of the reports referenced above from the DGCG the DTI published their Microgeneration Strategy (DTI, 2006) with a commitment that if the electricity supply companies do not set up a scheme for participation in the market by microgenerators, then the Government would use powers in the Climate Change and Sustainable Energy Act 2006 to impose one. The task to devise a scheme was picked up by the successor organisation to the DGCG, the Energy Networks Strategy Group (ENSG) who published an analysis of options and recommendations (ENSG, 2007).

At the time of writing one of the simpler ENSG recommendations, that a single MPAN be used to cover both import end export from a domestic installation, has been rejected by the BETTA governance and change control process. An alternative proposal (Elexon 2007) has been accepted into the process, that a "pseudo MPAN" be created for each supplier at each Grid Supply Point[3], to which the aggregated microgenerator export in the region for that supplier would be assigned for settlement. There is no guarantee that this new proposal will succeed, as there is clearly a lack of consensus in the industry, so an imposed solution may yet be required.

A further complication to the payment process arises from Renewable Obligation Certificates (ROCs). These are allocated by Ofgem for each MWh of renewable electricity generated. Electricity suppliers are obliged to obtain a certain number of ROCs in a rising proportion to the MWh they supply (currently about 7%) or pay a buyout price. This gives ROCs a value of about £45, and in principle they are obtainable for a domestic scale generator because anything more than 499kWh per year is rounded to the nearest MWh. However, they are only awarded on the actual output of the generator, export metering is not relevant. This need for additional metering combined with the complexity of the ROC registration and trading process means few

[2] Metering Point Administration Number
[3] A point at which electrical energy flows for a region are aggregated for balancing purposes.

small generators currently benefit. This illustrates the scope for improvement in metering processes as recognised in the first aim of this thesis.

2.6 The Research Context of Domestic Energy Management

This section reviews the more direct antecedents and peers of the present research in the area of domestic energy management and control, against which incremental progress is claimed in later chapters. The main strands of research that are recognisable in the literature comprise:

- The patterns of energy consumption in the domestic sector and attitudes of consumers towards its use and the need for greater efficiency.
- Specific technologies for domestic energy conversion such as micro CHP.
- Methods for demand side management of electricity use and integration of small scale electricity generators into the existing electricity distribution system, and distribution innovations such as microgrids.
- The human factors around provision and use of heating appliances in the home, particularly in relation to fuel poverty and efficiency.

Each of these topics is reviewed in turn below followed by a summary of the relevant gaps that were identified in existing research. Gaps were considered relevant if they could be filled by analysis of data collected from the test bed, and the findings from the analysis would contribute to the aims of this thesis.

2.6.1 Consumer energy use

Household energy consumption comprised 30% of UK energy use in 2004 (DTI, 2005), and is on a rising trend from 25% in 1970 (Shorrock & Utley, 2003). The exergy efficiency of household energy use is quite low and has 24% of the total UK scope for improvement, as shown in Figure 2-3.

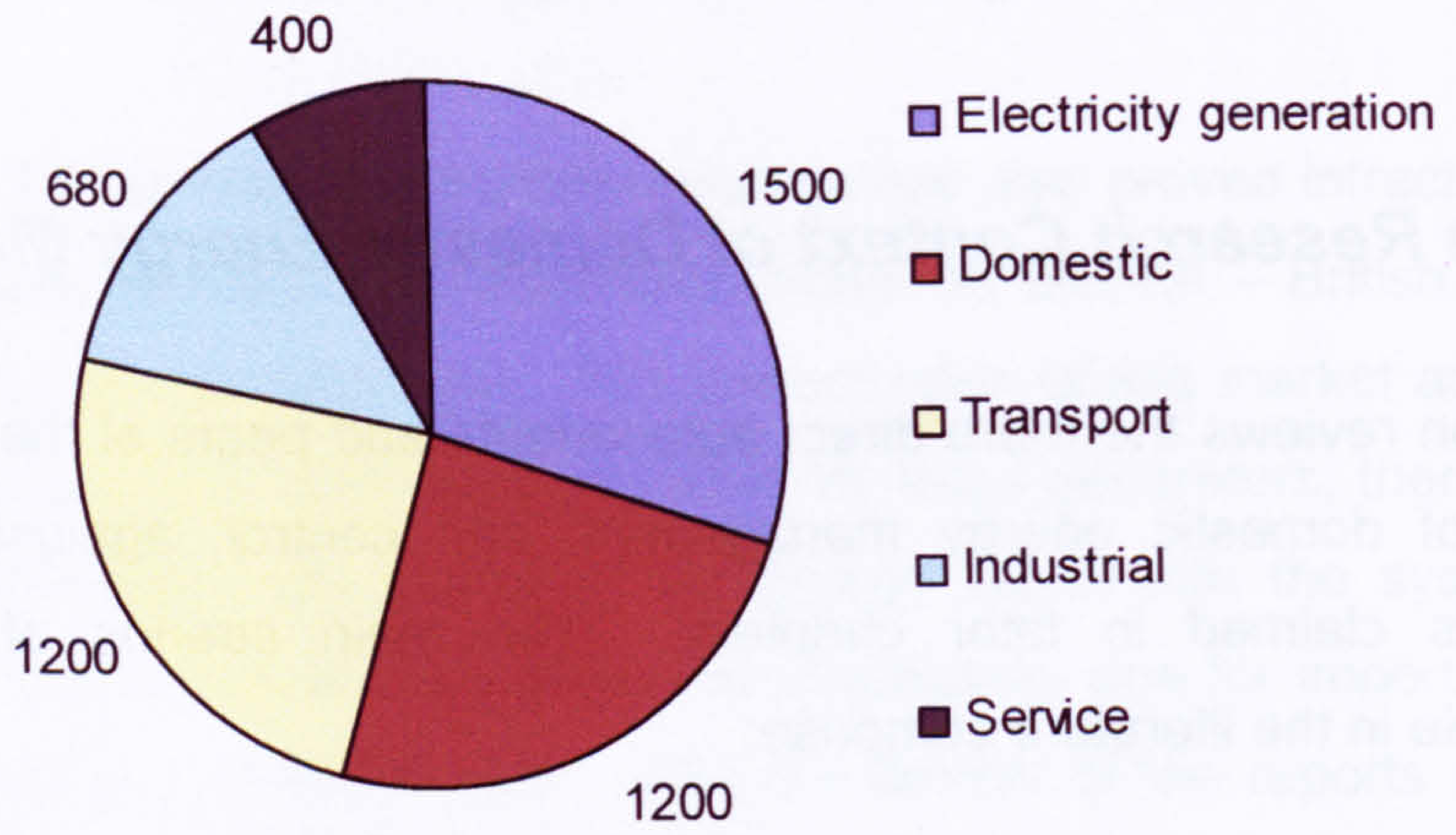

Figure 2-3 Annual potential in PetaJoules for exergy improvement in UK by sector (Hammond & Stapleton, 2001)

Domestic exergy efficiency is poor because typically homes acquire high exergy sources of energy, such as electricity or natural gas, and use them for low exergy purposes such as space heating, which simply require maintenance of a small temperature difference between the space and the ambient environment. Improvement can come only through more sophisticated energy conversion devices such as heat pumps. However, few consumers are likely to buy new energy technologies that are not immediately cost effective because only "initiators" driven by "accomplishment" will do this, and they represent less than 15% of the total possible buying population (Faiers 2007).

Even if an economic advantage is clear, before making a purchasing decision consumers usually apply two additional tests referred to in the literature as "compatibility" and "complexity". Compatibility describes how consistent the product is with the individual's values, attitudes, and behaviour. Complexity reflects how difficult it is to understand the principles of the product and the way in which it delivers benefits. The product must fit in with the consumer's lifestyle and the complexity must be within his or her threshold of knowledge and understanding. These findings indicate that to attain a large market penetration an energy management product must ideally be low cost, "cool" i.e. fashionable, and very simple to use. The iconic iPod is the classic example of a product that satisfies all these criteria.

The difficulty of engaging consumer interest in energy efficiency is brought out in a review paper by Graham (2007) who offers the summary:

> "Economists find it puzzling that consumers do not appear to act rationally in relation to energy efficiency improvements, given the economic, social, and environmental gains that can easily outweigh the costs. Many studies have explored this paradox, and shed some useful light on it. There remains considerable scope for further public engagement in this area".

One area where useful light has been shed is the need to improve the information available to consumers – this aspect is examined in 2.6.4. However, even when consumers do improve the energy efficiency of their homes, the environmental benefits are diminished because for most households the resulting financial savings are re-invested in other energy consuming activities or goods, or simply increased comfort or wastage. This is known as the rebound or take-back effect. Its impact is clearly important to policymakers considering the usefulness of subsidies for insulation improvements, but it is difficult to assess – a review paper by Dimitropolous (2007) draws together a wide range of economic studies that have attempted to quantify this effect and have arrived at figures between 15% and 350% for the ratio between the additional energy consumed through rebound and the original energy saving. The higher figures in this range are obtained when effects are traced throughout the economy at a national or global scale. He highlights a consensus from several major UK and Netherlands studies at about 27% for the effect at a national scale, but also points to a tendency for the rebound to increase in the longer term.

This offsetting increase in dissipation of energy arising from any localised efficiency improvement is exactly what would be expected from the principles of non-equilibrium thermodynamics set out in 2.2, as is the difficulty of quantifying it given the widely varying nature of the gradients and boundary conditions involved. Two useful conclusions can be drawn for this thesis. Firstly, efficiency improvements alone are inadequate and uncertain as a measure for reductions in carbon emissions, so Government policies will also have to encourage technologies that provide low or zero carbon energy inputs to the domestic environment, such as those discussed in the next section.

Secondly, the proposed ecological model for energy management implies that it should be possible to diminish the rebound effect (from a policy perspective) while respecting the iron laws of thermodynamics, with a control system that captures some of the energy saving before it is dissipated. For example, a family in a very well insulated home may tend to be careless with their heating settings because the cost to them is insignificant relative to their income. An intelligent control system that took energy saving decisions on their behalf while providing acceptable comfort could fill the niche presented by their behaviour in their domestic "ecosystem". By adding information the exergy in energy that would otherwise be wasted is preserved for potentially better use elsewhere – but no reliable claim can made that it will truly be saved. This concept is explored further in 2.6.4.

2.6.2 Low and zero carbon technologies

Research relating to low and zero carbon technologies (LZCTs) for domestic use is of interest to this study to indicate the current and future capabilities of devices that may be placed under control or supervision by the management system. Where an example of an LZCT forms part of the test bed a more exhaustive research review has been performed to ensure the instrumentation is capable of acquiring data of interest and to look for gaps in current research that might be filled. The LZCTs covered are as follows, of which the first three are installed in the test bed:

- Micro CHP
- PV
- Solar water heating
- Micro wind power
- Heat pumps.

CHP has long been recognised as a method for improving thermodynamic efficiency, since converting chemical fuels into both electricity and heat simultaneously in roughly the proportions both are required is inherently more efficient in Second Law terms than using a separate combustion process for each. However, heat cannot be transported very easily, so CHP has generally been limited in the UK to industrial sites or hospitals where there is a large and sustained local heat demand. There are also cultural factors limiting conventional CHP which are discussed fully in Chapter 4. Micro CHP has the potential to overcome these constraints by supplying heat and electricity from a physically compact, gas-fuelled, equipment with energy outputs suitable for a home or small office. The devices now on the market, e.g. Whisper tech (2003), combine a Stirling or internal combustion engine driving a generator with heat exchangers similar to a conventional condensing boiler. Micro CHP units employing fuel cell technology are now at an advanced stage of development e.g. CeresPower (2007). These oxidise the natural gas fuel using a catalysed electrochemical process that produces both heat and electricity; they are potentially more reliable, compact, and easier to manufacture than a micro CHP with a mechanical engine.

Several studies have sought to investigate the economics, potential take-up, and performance trade-offs of this technology. Harrison & Redford (2001) were the first to publish a clear case for the practical large scale viability of micro CHP in the UK. Their analysis showed that the extra cost to the consumer of a micro CHP over a conventional condensing boiler would be paid back within 3-4 years, and that each unit would reduce household CO_2 emissions by about 1 tonne per annum. Crozier-Cole & Jones (2002) performed a detailed analysis of the UK housing stock to determine those suitable for micro CHP and gave a central estimate of 13.5 million households i.e. about 56%. They also highlight the benefit of an energy service contract as a vehicle for supplying micro CHP to consumers, and the importance of establishing a stable payment mechanism for export electricity as discussed in 2.5.

Newborough (2004, Peacock & Newborough 2005) examined the detailed relationship between the relative electrical and thermal efficiency of the micro CHP, the consumer's electrical load, and CO_2 emissions. He confirmed the potential for reduction in CO_2 emissions indicated by Harrison and Redford but showed they are sensitive to the proportion of electricity generated that is exported and when it is generated. Emissions are reduced if generation matches demand peaks.

All these papers are based on computer modelling of micro CHP performance; the only paper available at the start of the present study giving practical results was from Entchev *et al* (2004). This paper reported results from a Canadian research house (i.e. with simulated occupation) whose construction (wood frame) electrical load (20kWh per day), size (210 m^2) and heat distribution system (warm air circulation) were wholly dissimilar to typical UK practice. A clear gap was evident in the literature for a paper publishing the actual performance of a micro CHP in a real home with construction materials, and a heating system, representative of the UK housing stock. Data was needed to support detailed analysis of the match between electricity generated and electricity demand, and allow overall performance to be compared with the modelling studies. Subsequent to most of the present research, the Carbon Trust published a report on a large scale trial of micro CHP which included the test bed device (Carbon Trust 2007) – its findings are discussed in Chapter 3.

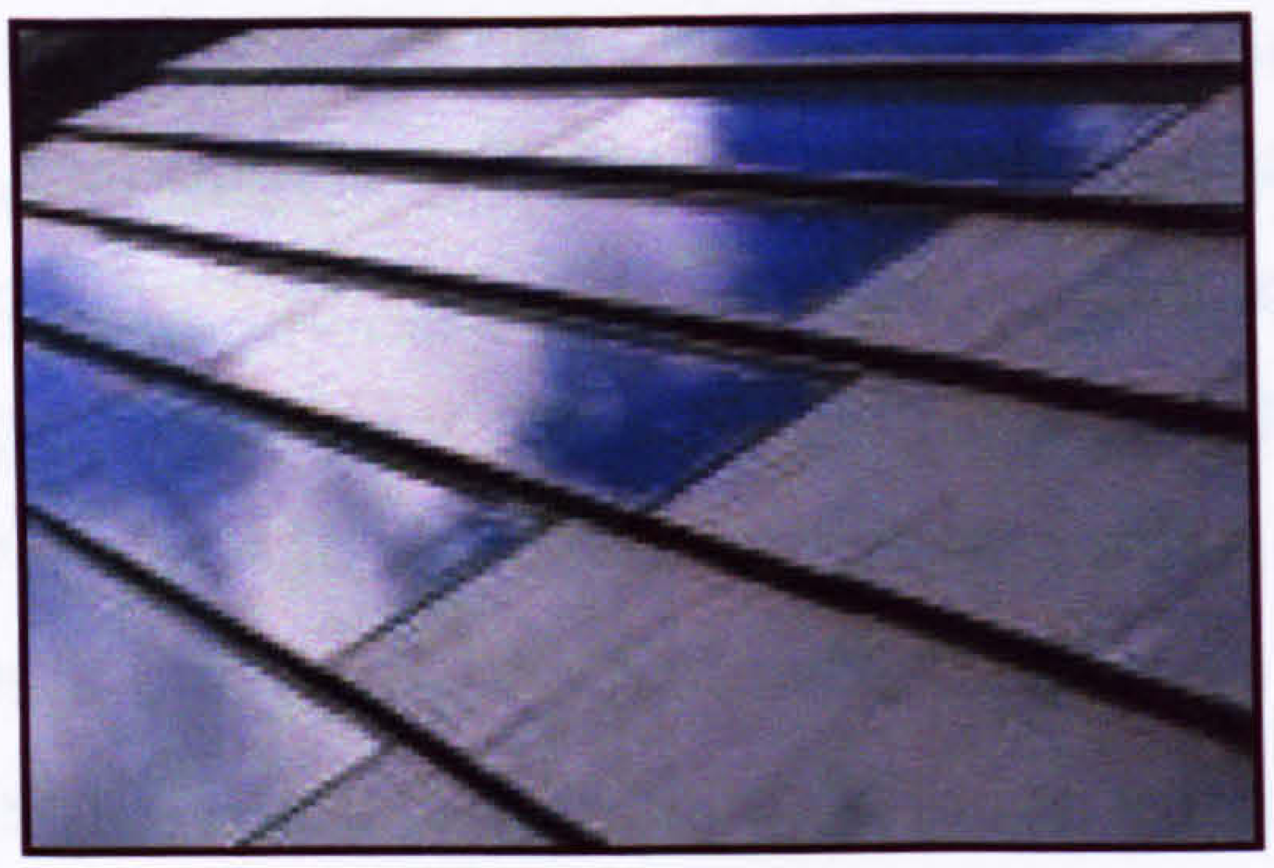

Figure 2-4 Solar photovoltaic roofing tiles (Solar Century 2007)

By contrast the performance of solar photovoltaic generators is very well understood and predictable for any location and orientation, as long as the efficiency of conversion from insolation to electrical energy is known for the photovoltaic technology being used. Markvart (2000) provides a comprehensive treatment. Conveniently, in the UK insolation amounts to about 1000 kWh per m^2 per annum. Current PV panel conversion efficiencies are in the range 10-15% dependent on the technology, so when losses in power conversion from DC to AC are taken into account a rule of thumb is that 100 kWh per m^2 per annum of useful electricity can be produced at a favourable location (i.e. a south facing unshadowed roof with about 30° pitch). With installed cost falling albeit slowly, and the introduction of PV panels as roofing materials as shown in Figure 2-4, penetration of this LZCT can be expected to increase steadily particularly in the south and urban areas.

As domestic PV generators become more commonplace, research is turning to their impact on household behaviour and economics. The findings are slightly disappointing: for example Bahaj & James (2007) in investigating a group of social housing installations found there was little change in patterns of energy use even though improved financial savings could be obtained by matching appliance use to the mid-day output peak. This result points again to the importance of export payments to ensure economic benefits are obtained, while the limited consumer interest is part of the general pattern noted in 2.6.1 and further examined in 2.6.4.

Figure 2-5 Solar water heating collector (Solartwin 2007)

Solar hot water heating is the most popular LZCT currently in use in the UK with around 80,000 installations (Energy Saving Trust 2005). Its main properties from basic physics and published research are:

- The proportion of incident solar energy that is captured by a solar hot water panel (Figure 2-5) depends on the mean temperature of the water passing through it – as this rises the losses increase simply due to Newton's law of cooling. So the timing of any other energy input used to heat the water has to be carefully controlled so that the panel can pre-heat the water first.
- It is desirable for the water in the storage tank to stratify rather than be mixed, so that water at a higher temperature accumulates at the top ready for use, and cool water is available at the bottom of the tank to feed the panel (Grassie, 2002). This implies a low flow rate through the panel and storage tank so that turbulence is avoided.
- The savings in use of other fuels such as gas and electricity from a solar hot water system depend on careful management. For example, a gas or oil boiler should be turned off in summer when hot water can be largely provided by the solar panel, augmented where necessary preferably by an electric immersion heater (Thur, 2006).
- To prevent bacteria growing in hot water storage tanks a temperature of above 60 °C has to be sustained for at least half an hour every day (Armstrong, 2003). Where this is not achieved by solar heating, the necessary additional energy needs to be supplied by an auxiliary source such as an immersion heater or gas boiler. The time to deliver this additional energy should be chosen so that it adds most effectively to the solar input.

Because the output obtained from a solar thermal panel is so dependent on the pattern of hot water usage, it is clear that other management opportunities exist. For example, wet appliances could be scheduled to draw solar heated water at the optimum time. Because most such products currently on the market have a cold feed only, it would be necessary to install a thermostatic blending valve to provide a water supply that is limited to the maximum input temperature specified for the appliance.

These various management requirements for solar water heating are carried forward into Chapter 4. Given the low-tech and relatively low cost nature of this LZCT, and its near universal use in some Mediterranean regions (e.g. Crete), it deserves to be widely adopted. It is generally easier to integrate into domestic buildings than PV because a smaller roof area is required – about 2-3m^2 of panel aperture is sufficient to provide about 1000kWh of heat annually and is a reasonable match to summer hot water usage. If the panels are too large with respect to the volume of hot water storage available and the level of use, then the water temperature becomes excessive in summer leading to extra complexity in the installation to prevent boiling.

Figure 2-6 Micro wind generator (Windsave 2005)

Micro wind generation (Figure 2-6) is a technology where entrepreneurial manufacturers of turbine generators such as the Windsave (2005) have created products, and demand for them, in advance of any extensive research base indicating their likely effectiveness. Myers *et al* (2007) provide an analysis which shows that even in relatively favourable coastal or exposed locations the amount of electricity generated by an installation on a house will be quite small, because of the low elevation above ground that is possible (they assume 7m). For a 1kWp turbine (the Windsave) the best output was for an

Aberdeen location giving 460kWh per annum. A West Midlands location gave 158 kWh per annum. However, payback times are still better than PV and comparable with solar hot water systems because of the fairly low installed cost. Interestingly, this research also shows that a micro wind installation on a block of flats giving 25m elevation is a very good proposition, with up to 1500kWh from a 1kWp turbine.

These results, combined with the aesthetic limitations of wind generation (the turbine blades of a Windsave are 1.75m in diameter) suggest that this technology will not proliferate in urban areas, but will be taken up in coastal or rural locations, and for multi-occupancy buildings that can provide the elevation needed for optimum performance.

Figure 2-7 Air source heat pump (Marstair 2007)

Heat pumps are a form of thermodynamic heat engine where high exergy energy (normally electricity) is used to transfer heat from an external source such as the air or ground into a building with an accompanying gain in temperature. They are of particular interest in formulation of a long term energy strategy since they offer a credible, exergy-efficient, way of replacing the boilers that are the dominant source of space heating in UK homes with a LZCT that is not inherently dependent on fossil fuels. This of course assumes that the carbon content of grid electricity is successfully driven downwards as expected by regulatory and economic pressures.

Cockroft and Kelly (2006) have performed a comparison of the CO_2 emissions from various forms of micro CHP and air source heat pumps by modelling their use in a range of dwellings under present day and 2020 scenarios. The key features of their 2020 scenario are that all the buildings are insulated to current UK building regulations, and have better air tightness (infiltration limited to 0.5 air changes per hour), while the carbon intensity of UK grid electricity is reduced to 0.3 kg CO_2./kWh from the current level of 0.43 kg CO_2./kWh. Their finding is that the air source heat pump provides by far the best performance in the 2020 scenario, with twice the CO_2 savings relative to a condensing boiler than the micro CHP.

While the analysis by Cockroft and Kelly is open to challenge in some respects (their modelling of CO_2 savings from micro CHP takes no account of electricity exports and is not based on practical experience), if trends for improved insulation and reduced carbon intensity in grid electricity are sustained then heat pumps are certain to be widely used. They are particularly attractive for new houses because underfloor heating can be installed, which allows a lower temperature for heating water circulation giving a better coefficient of performance (the ratio between electricity input and heat output) than a system with wall radiators. They can also be constructed to provide a cooling function in summer, which consumers will consider an increasingly desirable feature as climate change takes place.

2.6.3 Demand side management and microgrids

The benefit of demand side management as outlined in 2.5 has been apparent to the electricity industry since the 1960s when the Economy 7 tariff was introduced to stimulate overnight demand for electricity from nuclear power stations which need to operate at a constant power level for reliability. A typical domestic installation exploiting this tariff when first introduced comprised a few electrically heated thermal storage units and an immersion heater, fed off a separate wiring circuit controlled by a timed switch limiting operation to the Economy 7 time interval (1 a.m. to 8 a.m.). When this form of heating was adopted on a large scale during the 1970's, the large change in demand at the start of the operating period became increasingly difficult to manage.

To mitigate this problem the radio teleswitch system (British Standards Institute 1993) was introduced in the early 1980s. This transmits switching times as a digital signal carried within the BBC Radio 4 broadcast on 198 kHz, with address codes allowing the population of storage heaters to be divided into up to 256 groups that can be started at different times. The system can also switch radiators on for a period during the day to top up the thermal charge. There have been proposals to extend the capability of the radio teleswitch system, to provide a cost signal and a weather forecast allowing the storage radiators to be charged precisely to match the expected thermal load e.g. (Hawley, 2000). These have not been adopted, partly because the low turnover and absence of growth in the installed base of radio teleswitch receivers does not draw in new technology, and also the ability of consumers to switch suppliers easily means contracts that permit demand management are not maintained (Kema, 2005). Consequently the usage of the existing teleswitch system is actually declining despite its potential value as a demand side management tool. The lesson from this experience is that combining control and metering functions in a single equipment that requires a particular form of wiring installation and is dependent on a specific form of supply contract is far too inflexible. Any improved system should have two properties:

- it should be capable of installation by householders or tradesmen on their own initiative without affecting any supply contract;
- it should allow any appliance to be controlled, not just storage radiators, but also, for example, freezers, tumble driers, immersion heaters, heat pumps, and micro CHP units.

The first requirement implies that control and metering functions must be separated, since electricity meters can only be installed by Distribution Network Operators (DNOs) or their metering agents. However, for consumers to be rewarded for demand management their electricity supply contract must have a time dependent tariff structure and time sensitive metering must be performed. Such "smart" metering is widely recognised as a facilitator for energy efficiency – large scale deployment is in progress in Sweden, Denmark, and Italy, and a substantial pilot programme has now been initiated in the UK (DEFRA, 2006).

With the advent of microgenerators it is clear that electricity demand management should take account of the availability of local sources of electricity as well as the issues around large scale generation discussed in 2.5. The methods by which this might be achieved are under active research with two main strands of investigation, one seeking to balance supply and demand at a district or campus scale, the other at the level of a building or household. The first of these is focussed on the microgrid concept. First proposed in its current form by Lasseter (2002), this aims to devolve the management of voltage and frequency stability to a localised low voltage grid with some level of local generator and demand controllability, combined with local storage and injection of energy from the national grid where necessary and possible. The electrical engineering techniques necessary to maintain voltage and frequency within statutory limits on a local distribution network with a large amount of renewable generation and a constrained grid connection are now emerging from demonstration projects such as that on Orkney (Scottish & Southern Energy 2004).

Abu-Sharkh *et al* (2006) examine the possibility that a community with sufficient penetration of micro CHP and domestic scale PV might be self sufficient in electricity with a quite limited amount of storage, when the complementary seasonal characteristics of each type of generator are considered. Their calculations indicate that the storage required would be about 2.7kWh per household, which is well within the capability of current battery technology. If practical, this level of self sufficiency would be a considerable step towards proving the feasibility of a micro grid in a typical urban environment. The use of local energy storage is also perfectly congruent with the organic optimisation model which this thesis aims to explore. However, the Abu-Sharkh paper is based purely on modelling, with no real-life data on micro CHP to support it. Validation of their finding concerning energy storage was identified as a research gap which could be addressed by analysis of data from the test bed. The methods employed to perform the analysis and the results are discussed in Chapter 3.

Two European research programmes are investigating demand side management that operates at the building scale and takes account of local generation. The first (Nestle, 2007) envisages electricity market prices being signalled to a controller which schedules loads in a way which reconciles user needs and local generators with the market signal. The second (Warmer 2007) is again price driven but envisages an auction process embedded in the software of the controller which matches local supply and demand. From the perspective of this thesis both these programmes have an important gap in that they are focussed on electricity generation and use. They are not easily adaptable to take account of all energy flows within a household. For example Nestle's scheduler and Warmer's auction will optimise the time when a washing machine or a micro CHP should operate with respect to electricity prices, but it is not clear how either might take account of the availability of hot water from a solar panel. So demand side management that is responsive to all the energy needs and sources within a household is identified as a gap. A more detailed discussion of the work by Nestle and Warmer is presented in Chapter 4 as part of the rationale for the approach adopted in the present study.

2.6.4 The human interface of energy controls

Consumers have problems with the current generation of heating controls. One study (Critchley *et al* 2007) has investigated the effectiveness of improvements to insulation and heating systems implemented under the Warm Front programme to address fuel poverty. It found that 25% of the homes surveyed are persistently cold despite the improvements, and reports:

> "However, a major residual problem was controlling the central-heating system. A third of all respondents over 60 reported difficulty with programmers, with a majority of these saying they were too complicated; *"I don't understand it," "I'm not very technical – unsure what to do."* There were three types of response; first leaving the system as originally set, *"I never touch the controls;"* second, asking friends, family members or neighbours to adjust the setting; third, resorting to manual settings, *"My husband switches it on when he gets up."* However, in [all] these cases, such coping strategies were evidently not successful in securing warm homes."

This is an important finding since the temperature threshold for defining a household as either cold or warm was that below which there is increased risk of circulatory and respiratory disease. The serious limitations of current controls (tiny displays, unusable switches, incomprehensible instructions) have also been identified by Ricability (2004), a research charity providing consumer information to elderly and disabled people. Often the usability of the control unit is further impaired by installation in a dark corner such as an airing cupboard, due to the need to hard wire it to the controlled device.

The effect of these usability problems on energy efficiency is illustrated by a Swedish survey of behaviour with respect to energy use in 600 households (Linden et al 2006), who found:

> "Problems of coping with chaotic, over complicated or unmanageable heating systems were also voiced in the interviews. "*No, we would not lower temperature when away during the daytime, well but in the weekend we are at home and we have small children and then one has to reprogramme once per week and that is completely....it is not possible.. it does not work...it is too troublesome*" (Young household in detached house)."

This survey also found that 38% of homes where the heating temperature could be lowered overnight did not do so, and that "more user friendly technology for adjusting indoor temperatures was a commonly proposed policy measure among those who did not currently lower their indoor temperatures". A similar survey comparing behaviour in Norway and Japan found that less than half of the Norwegian households reduced space heating temperatures overnight and 28% did not even reduce them when they left the house for holidays (Wilhite et al 1996).

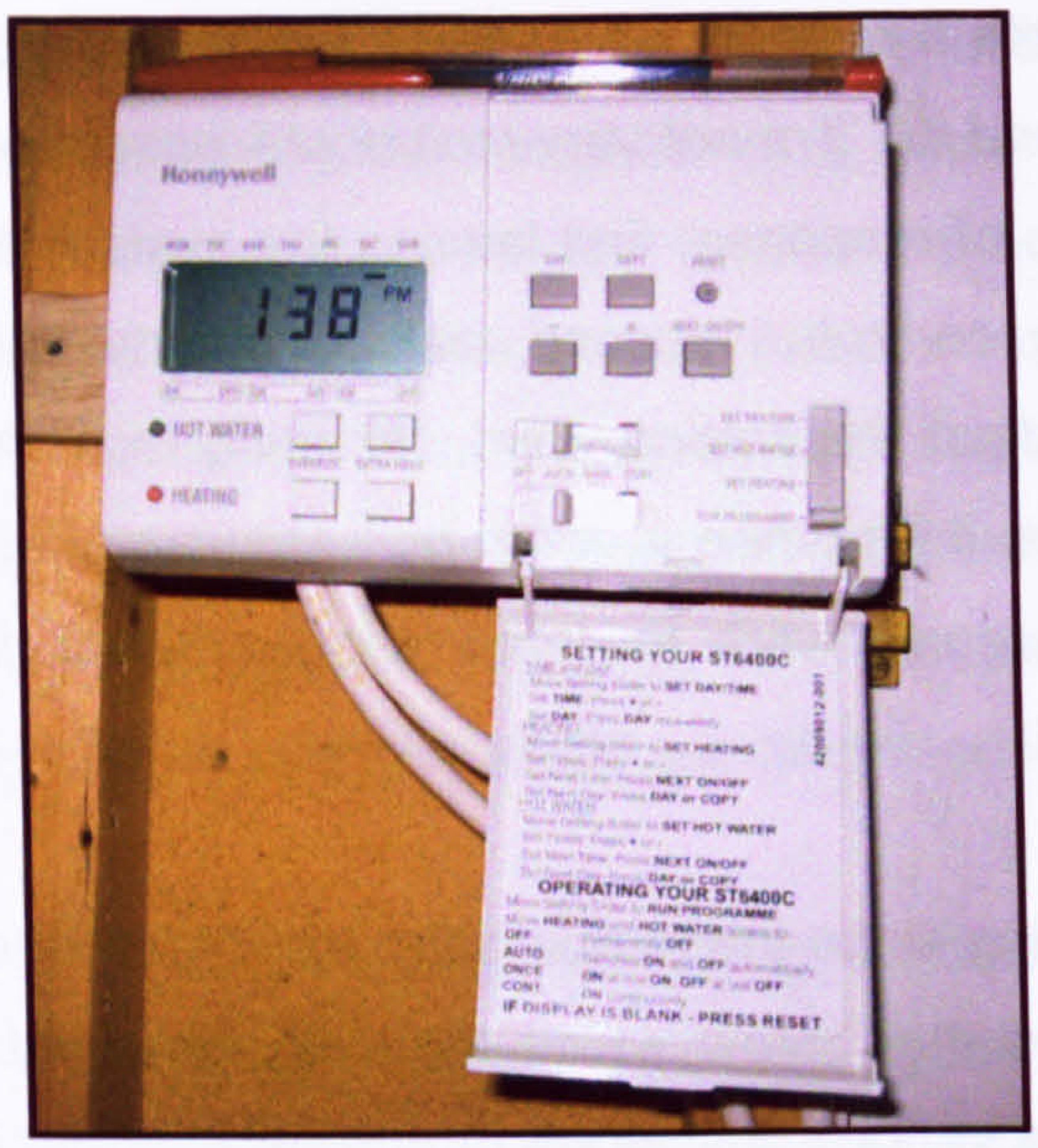

Figure 2-8 Heating timer unit

The real practical difficulties inherent in the current design paradigm for the majority of domestic control devices are illustrated by the Honeywell ST3400C "programmer" shown in Figure 2-8 (with a biro pen on top to indicate scale). This has been controlling the micro CHP in the test bed (described in Chapter 3) up to the point when a prototype replacement was available from this research. It is typical of the products available at any plumber's merchant – its input interface comprises 10 buttons and 3 sliders having four positions, and it responds on a small screen 50mm by 20mm. It takes 4 pages of small print and diagrams to describe how to use the buttons and sliders simply to set the times at which heating and hot water should be available – the text visible on the drop-down cover is a short form guide to prompt those who have mastered the main handbook. Once these times are set, it acts as a gate which allows heat demand signals from room and hot water cylinder thermostats through to the micro CHP during "on" intervals, and blocks them during "off" periods.

It takes motivation, skill, and patience to read the instructions carefully and use them to configure a workable and reasonably efficient programme on this device. Anyone using it is tempted to just use the manual on/off function on the sliders, particularly when they have lost track in the intricate sequence of button depressions needed to set times.

The only alternatives to this kind of product currently available are even more complex, being derived from building management systems designed for large industrial and commercial premises. They are targeted at wealthy consumers who desire a "high-tech" ambience in their homes, and are interested in having the drawing of curtains motorised or have large houses for which multiple time and temperature control zones do have some energy saving merit. A good exposition of the capability and market for this kind of system is the Smart Controls (2007) planning guide. These systems, while costly, have introduced to the market useful refinements such as weather compensation of heating. This adjusts the temperature of circulating water dependent on the heat load so that the return temperature is as low as possible consistent with comfort. A low return temperature improves the efficiency of condensing boilers and heat pumps. This technique is now being adopted in the mass market.

Another strong research finding is that providing better information to consumers on their use of energy results in a reduction in total consumption. This can take various forms such as better billing information or displays of current consumption driven from a "smart" meter. A research review for DEFRA[4] by Darby (2006) of a wide range of UK and international studies shows that long term average energy savings of 5 to 15% are obtained by providing a display of electrical load. Without this kind of stimulus, most people are really not interested in energy saving whatever its place on the political agenda. Darby provides some illuminating quotes from interview-based studies:

> "Energy and power are not terms within the natural language of mainstream householders. Gas and electricity operate at the level of the subconscious within the home... Whilst there does seem to be some latent cultural guilt about the notion of waste... there appeared to be virtually no sense of being able to actively and significantly reduce energy consumption in the household."

> "*We can't be using that much...It's just the two of us in this two-bed flat. I am out all day...and we are on income support. I just don't know how the bills are so high... I think there is something wrong with them.* - Londoner in her 30s, whilst in broad daylight lights were on in most rooms, a TV and radio were playing in an unoccupied bedroom, and all appliances in the sitting room were on standby."

[4] Department for Environment, Food, and Rural Affairs

So the desirable features for the human interface of an energy management system as indicated by these research findings are:

- Extreme simplicity in use including a convenient location.
- Large robust buttons or switches with intuitive functionality and feedback as to their effect.
- Clear displays.
- Provision of information on current energy consumption and cost in an easily understood form.

No evidence has been found of ongoing research or development into products that address all these issues simultaneously, although the last requirement for better information continues, in isolation, to be the subject of extensive research in the context of "smart" meter trials. Existing control systems are clearly far too complex in operation for important groups of consumers, yet the science discussed in 2.1 shows that high efficiency implies greater complexity and diversity within the energy conversion and consuming devices to be managed. A radical approach is needed to the design of the user interface which will allow the underlying complexity to grow unconstrained by human limits, and at the same time stimulate consumer engagement with energy efficiency.

The complexity of the user interface is largely governed by the amount of information that the user has to provide. This can only be reduced if the device obtains that information by itself. In practice this means making decisions, such as the times that a heating device is switched on and off, that make assumptions affecting the comfort or convenience of the user. This raises an ethical question as to the extent to which it is appropriate for the system to make decisions which, as illustrated by the quotes in this section, the user is either unable (through incapacity) or unwilling (through idleness) to make for themselves. Interestingly the results from the *Warm Front* study identified a group of people who actually like being cold, so a system taking decisions on their behalf would have to allow their preference to be expressed in a simple and accessible way even though their health might be slightly impaired as a result. However, because in broad terms the impact of global warming will be most painful on those who have done least to cause it, this study takes the view that it is appropriate for a system serving the interests of a relatively wealthy population in a temperate country to take decisions which intervene quite strongly in the lifestyle of the user, in the interests of energy efficiency. This is consistent with the ecosystem model where localised excess energy flows attract other species to capture and use or store the exergy. The practical implications and trade-offs arising from this approach are explored in Chapter 5.

2.6.5 Summary of research gaps

This review has identified several gaps in published research that could be addressed by the present study using the technical resources of the test bed that are directly relevant to the aims and hypothesis. These are:

- Measurement of micro CHP performance in a real UK household, and comparison of these results with those assumed or obtained by published modelling studies.
- Examination of the feasibility of a microgrid based on domestic PV, micro CHP, and limited electricity storage.
- Development of a domestic demand side management technique that takes account of all energy sources and sinks within the household, not just electricity.
- Realisation of human interfaces for energy control that improve on the manifest limitations of current products, and can hide increasing levels of complexity while providing essential information that motivates efficiency.

In Chapter 3 results are presented that fill the first two gaps, and in Chapters 4 and 5 a concept and practical realisation is set out for a domestic energy management system that responds to the last two gaps.

3 TEST BED

3.1 *Concept of Use*

In order to ensure the ideas developed in this study are practical and realistic, example equipments representing several low and zero carbon technologies have been installed in an occupied family house, accompanied by instrumentation to allow their performance to be monitored and overall energy flows associated with the building to be measured. The equipments have therefore been subject to the practical constraints and human factors arising from real life over several years, which would be hard to simulate accurately in a laboratory. The house, while larger than the UK average, is typical in its construction methods and materials of houses built in the 19th and 20th centuries. The data from this test bed have been collected and analysed with two purposes in mind:

- To add to the body of knowledge concerning the operation of these technologies in the domestic environment, particularly where gaps are evident in existing published research as discussed in the previous chapter.
- To look for attributes of the technologies, individually or in combination, which should be taken into account by a management system which seeks to optimise their use. In effect these attributes generate requirements for the energy management system. The resulting requirements are summarised in Chapter 4 in combination with those arising from Chapter 2, and used as the basis of a system design in Chapter 5.

A prototype of the proposed energy management system has been installed and tested in the house.

3.2 *The Household*

To provide a context for the measurement data from the test bed, and the results of analysis that are reported later, a short description of the building and the lifestyle of its occupants is appropriate. The north façade of the house is shown in Figure 3-1, and the south facing aspect in Figure 3-2. It is located on the eastern side of Cheltenham, Gloucestershire, and was built in 1910 as a tenant farmer's house, of local brick with Cotswold stone trimmings. It is an early example of a house with a cavity wall; the cavity is now filled with insulation in the form of polystyrene balls. It has four bedrooms, two reception rooms, and a total floor area of 133 m^2. At the rear is what looks like a single story extension, but is in fact the dairy of the original farm now integrated into the house to provide an enlarged kitchen and a utility room. The flat roof of this part of the house provides a platform for solar hot water and photovoltaic collectors.

The permanent occupants are what might be called "empty nesters", so most of the time there are only two people around, with intermittent occupation during daytime, but occupation surges to 4 or 5 or more for some weekends and holidays when children return home or visitors are entertained.

The thermal properties of the house are indicated by the parameters in Table 3-1. These have been calculated as a "best fit" to the thermal response of the house as measured at a single point (the room temperature thermostat located in the ground floor hallway). In effect the heat loss rate is an aggregated thermal transmittance coefficient for the whole house, and the specific thermal capacity is an aggregated specific heat. The methods used to calculate these values are described later in section 5.5.

Parameter	**Value**	**Notes**
Specific thermal capacity	16 kWh / °C	Measured at 20 °C
Heat loss rate	365 W / °C	Measured at 20 °C

Table 3-1 Building thermal parameters

Figure 3-1 North facing aspect.

Figure 3-2 South facing aspect.

3.3 *Micro CHP*

A micro CHP unit installed in the garage and supplied with mains natural gas, as shown in Figure 3-3 below, provides the primary source of space and hot water heating for the house. It delivers heat through a conventional pumped hot water system (shown schematically in Figure 3-4) with 14 radiators in 12 spaces - ground floor radiators have thermostatic radiator valves. Domestic hot water is provided by indirect heating of a 90 litre insulated tank. The micro CHP is a pre-production Whispergen device provided under a Carbon Trust sponsored trial, with instrumentation measuring electrical energy input and output, heat output, and gas consumption at 5 minute intervals. Internal and external air temperatures are also measured at the same frequency.

For the trials reported in this chapter it was controlled by a simple timer and single room thermostat located in the downstairs hallway of the house. These units[5] were typical of those currently supplied to the plumbing trade for "wet" central heating systems. Once a prototype controller according to the concept of this thesis was available towards the end of the study it replaced these simple controls as described in Chapter 5.

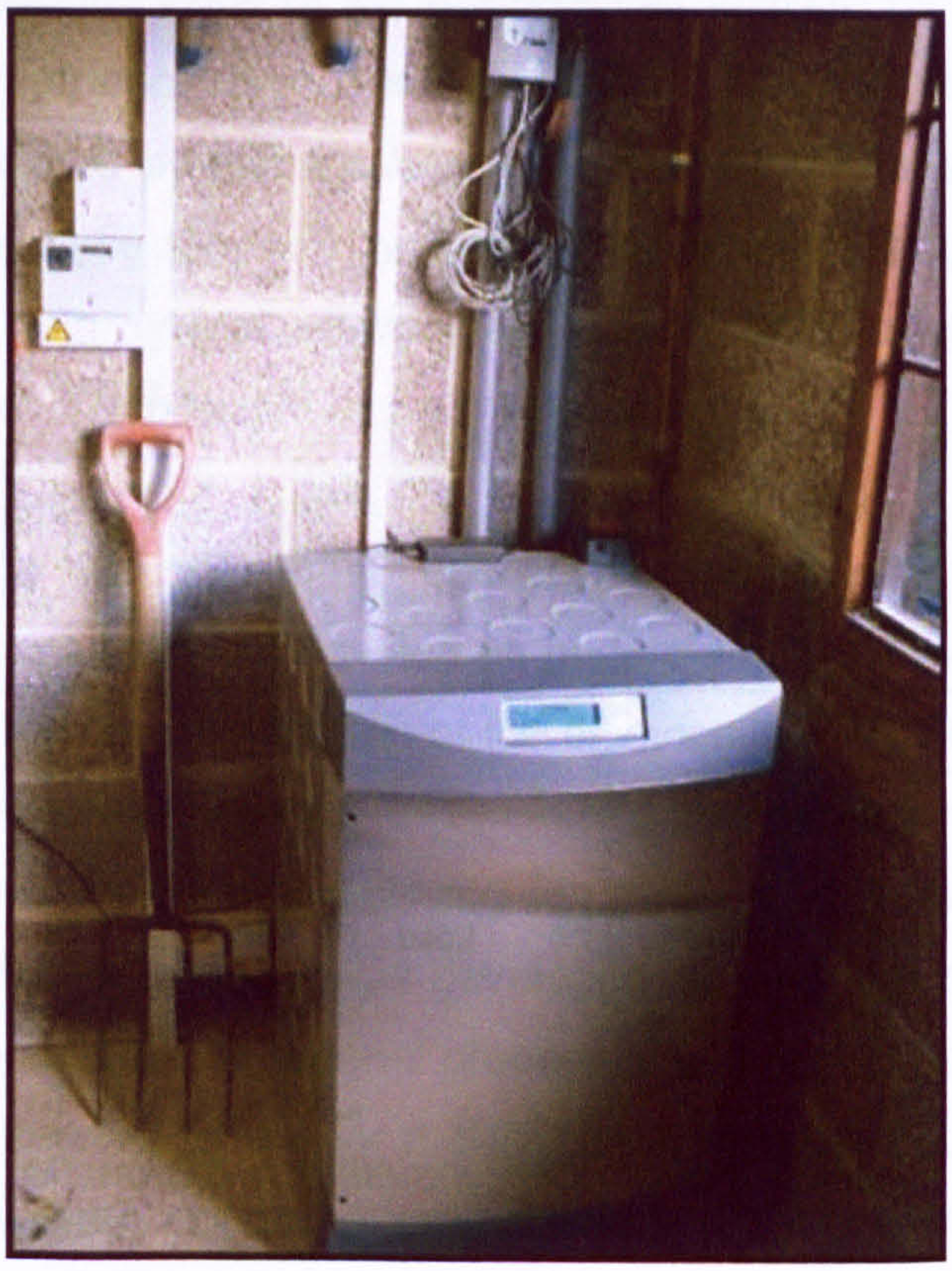

Figure 3-3 Micro CHP unit

[5] Honeywell ST3400C timer and Drayton Digistat SCR thermostat

The maximum heat output in normal operation is 8 kW, which is associated with a net electrical output of 1 kW from a generator driven by a Stirling engine. It is capable of lower levels of heat and electrical output but these are usually only produced briefly while the device ramps up from standby to reach and maintain maximum output - the level of highest thermal efficiency. A comprehensive specification is at Whisper Tech (2003).

It can be seen that the 8kW heat output is actually insufficient to meet the heat load of 365 W / °C at the usual reference external temperature of -1°C when domestic hot water heating requirements are included. This is a desirable situation for a micro CHP, because it ensures that at the mild external temperatures typical of the UK heating season, it is operating for a sufficient length of time to generate useful amounts of electricity. The electrical load from lighting and entertainment appliances normally provides an adequate top-up ensuring temperature set points are achieved. Figure 3-5 illustrates a typical electrical output profile for the micro CHP plotted with the house electrical load.

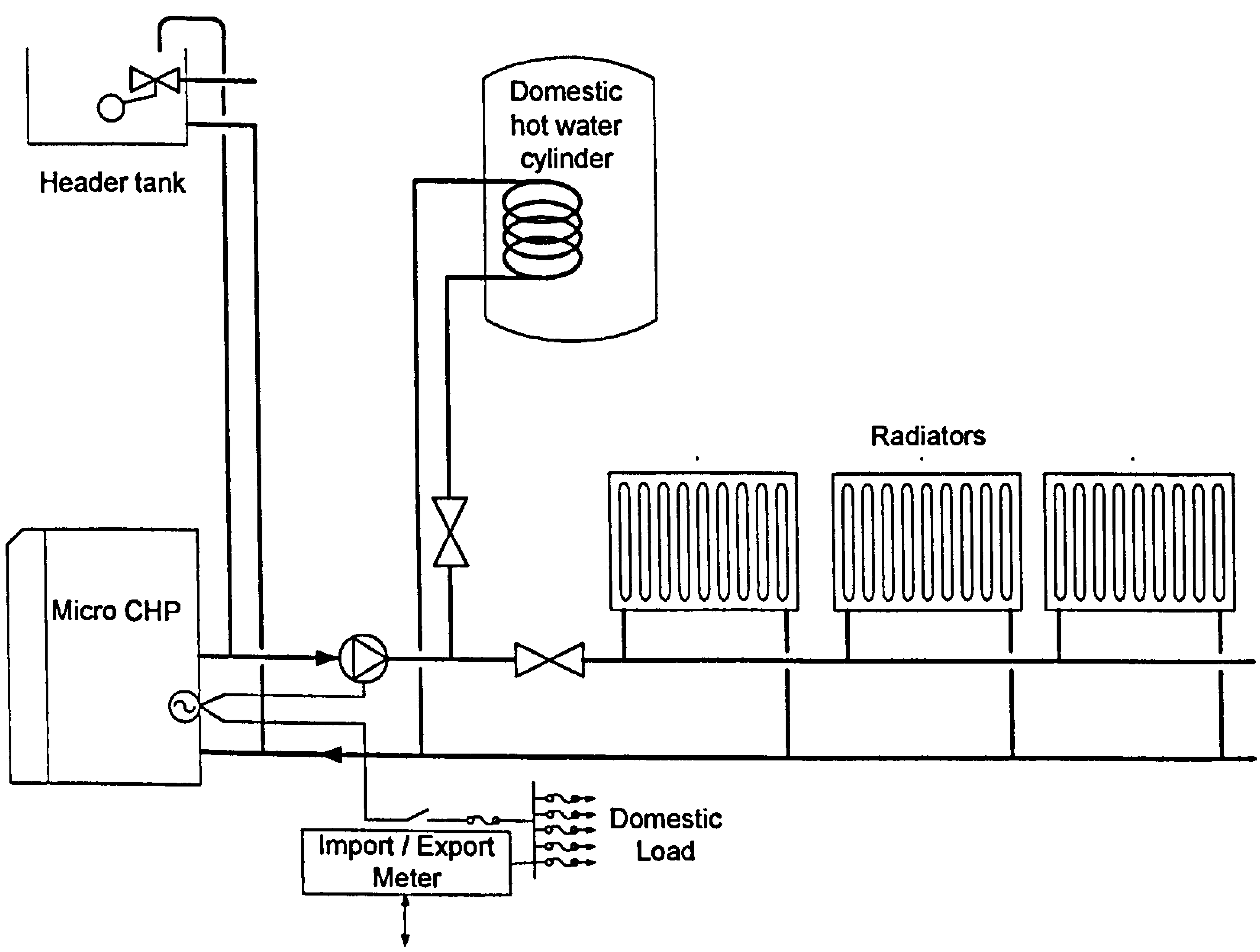

Figure 3-4 Micro CHP installation schematic

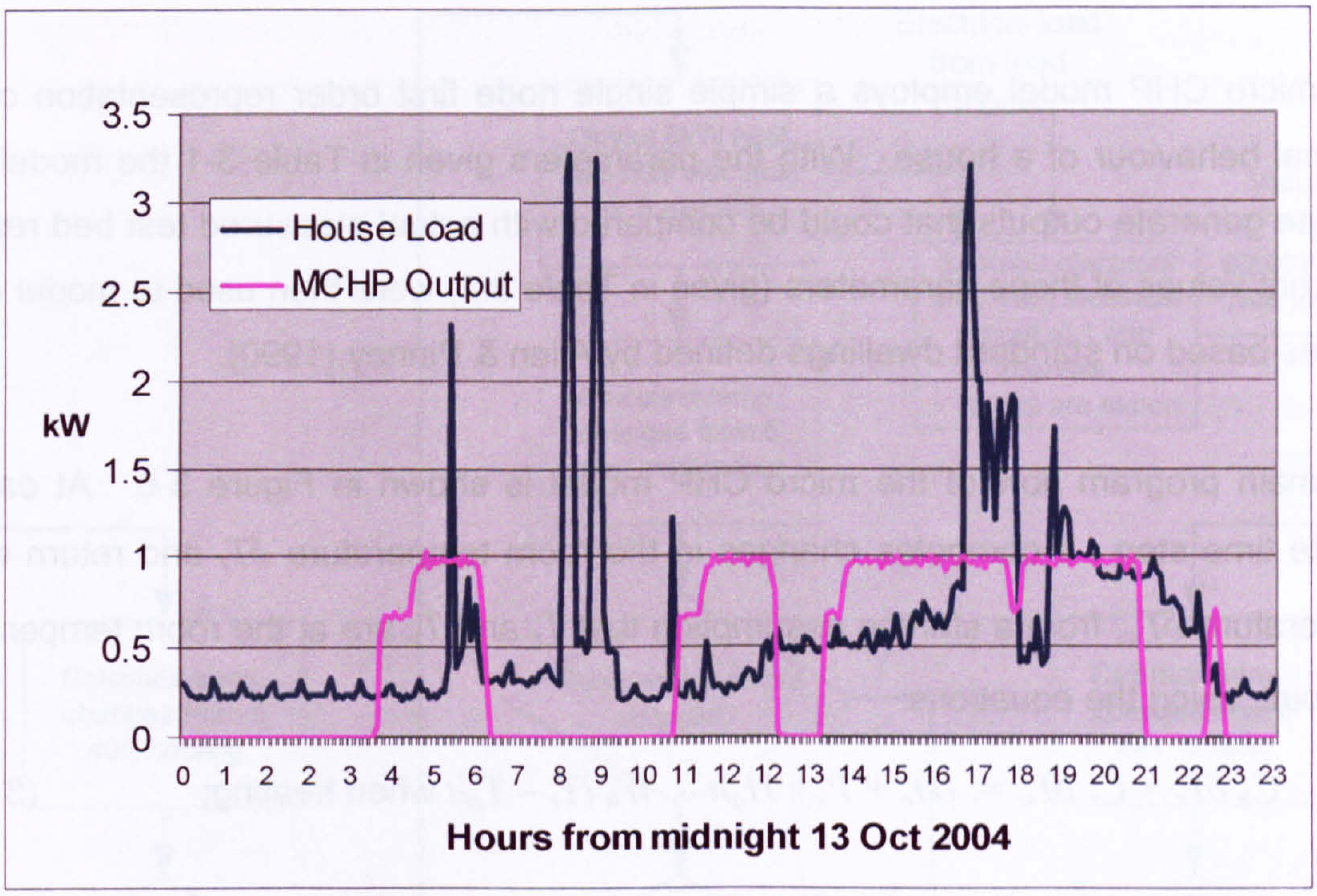

Figure 3-5 Typical Micro CHP output over 24 hours

The overall efficiency of the unit (i.e. the sum of measured net electrical and useful heat outputs, divided by calorific value of the gas used as advised by the supply company) was 82% in normal operation over a winter period. This efficiency figure treats the electrical power consumed by the circulating pump and the fans and electronics within the unit as losses, because they are largely met by the internal generator, so it is not directly comparable with typical efficiencies around 90% quoted for conventional condensing gas boilers which ignore these electrical loads.

Following installation in August 2004, the operation of the unit was closely analysed over the subsequent heating season, to develop an understanding of the interaction between the thermal load and the time distribution of the electrical output. From this it was hoped to identify opportunities and methods for optimising the management of such devices and their integration with the electrical distribution system. In order to generalise results from this single installation a model was developed allowing the electrical output to be predicted in houses with different thermal properties and occupation levels. So that the levels of electricity exported to the local distribution network could be predicted, this model was integrated with another model (Stokes, 2005), which predicts domestic electricity demand dependent on time of day and year, house size, appliance population, and occupation levels. This also allowed the modelling of thermal load, employed to compute the running time (and hence generator output) of the micro CHP, to take account of the heat dissipated by appliances and lighting.

The micro CHP model employs a simple single node first order representation of the thermal behaviour of a house. With the parameters given in Table 3-1 the model was used to generate outputs that could be compared with actual measured test bed results. Different values of these parameters (given in Table 3.2) were then used to model other houses based on standard dwellings defined by Allen & Pinney (1990).

The main program flow of the micro CHP model is shown in Figure 3-6. At each 5 minute time step t it computes changes in the room temperature δT_r and return water temperature δT_w, from a starting assumption that T_r and T_w are at the room temperature set point, using the equations:

$$C_h\,\delta T_r = C_r\,\delta T_w = (H_c + P_e + H_o)t - W_h\,(T_r - T_e)t \text{ when heating;} \qquad (3.1)$$

$$C_h\,\delta T_r = (P_e + H_o)t - W_h\,(T_r - T_e)t \text{ and} \qquad (3.2)$$

$$C_r\,\delta T_w = [(P_e + H_o)t - W_h\,(T_r - T_e)t](T_w - T_r)/(T_{ws} - T_{rs}) \text{ when cooling.} \qquad (3.3)$$

Where C_h and C_r are the specific thermal capacities of the house and the radiator circuit, H_c is the heat output of the micro CHP, P_e is the mean electrical load over the time step, H_o is the heat output from the occupants, W_h is the specific heat load of the house, T_e is the external ambient air temperature, and T_{ws}, T_{rs} are water return and room temperatures at the time heating stopped. Different values of C_r are used when the micro CHP is operating (i.e. the system is heating), and when it is off (i.e. system is cooling), to reflect the different thermal capacity of the radiator system when the water content is being pumped and when it is static.

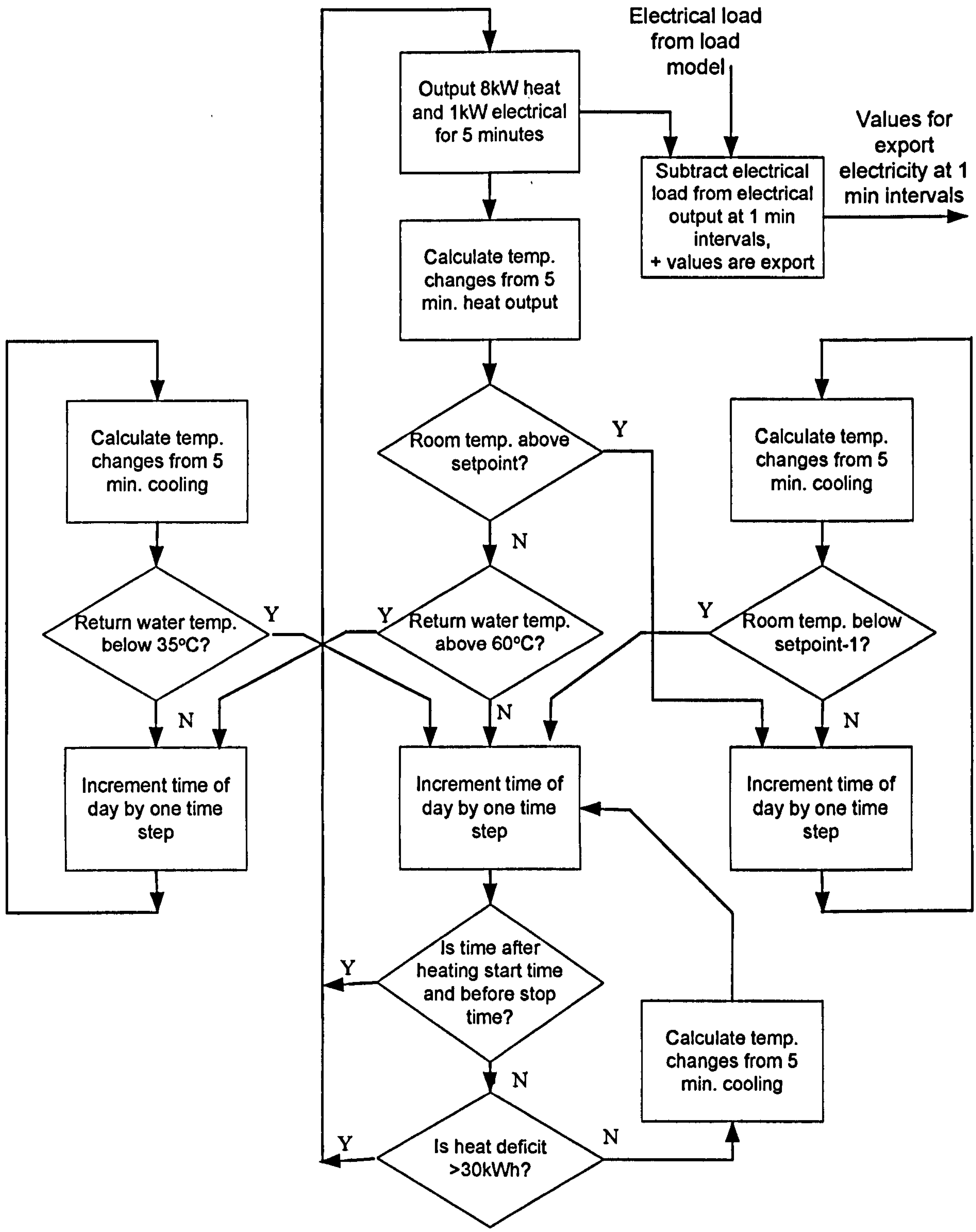

Figure 3-6 Flow diagram of micro CHP model

The micro CHP and electrical demand models were validated by comparing actual measured exports with the predicted export levels obtained by configuring the micro CHP and load models with the thermal parameters, occupation levels, and external temperatures for the test house. Figure 3-7 is a scatter plot of the modelled and actual electricity export for each month in the 8 month period from September 2004 to April 2005. The correlation coefficient (r^2 value) is 0.96.

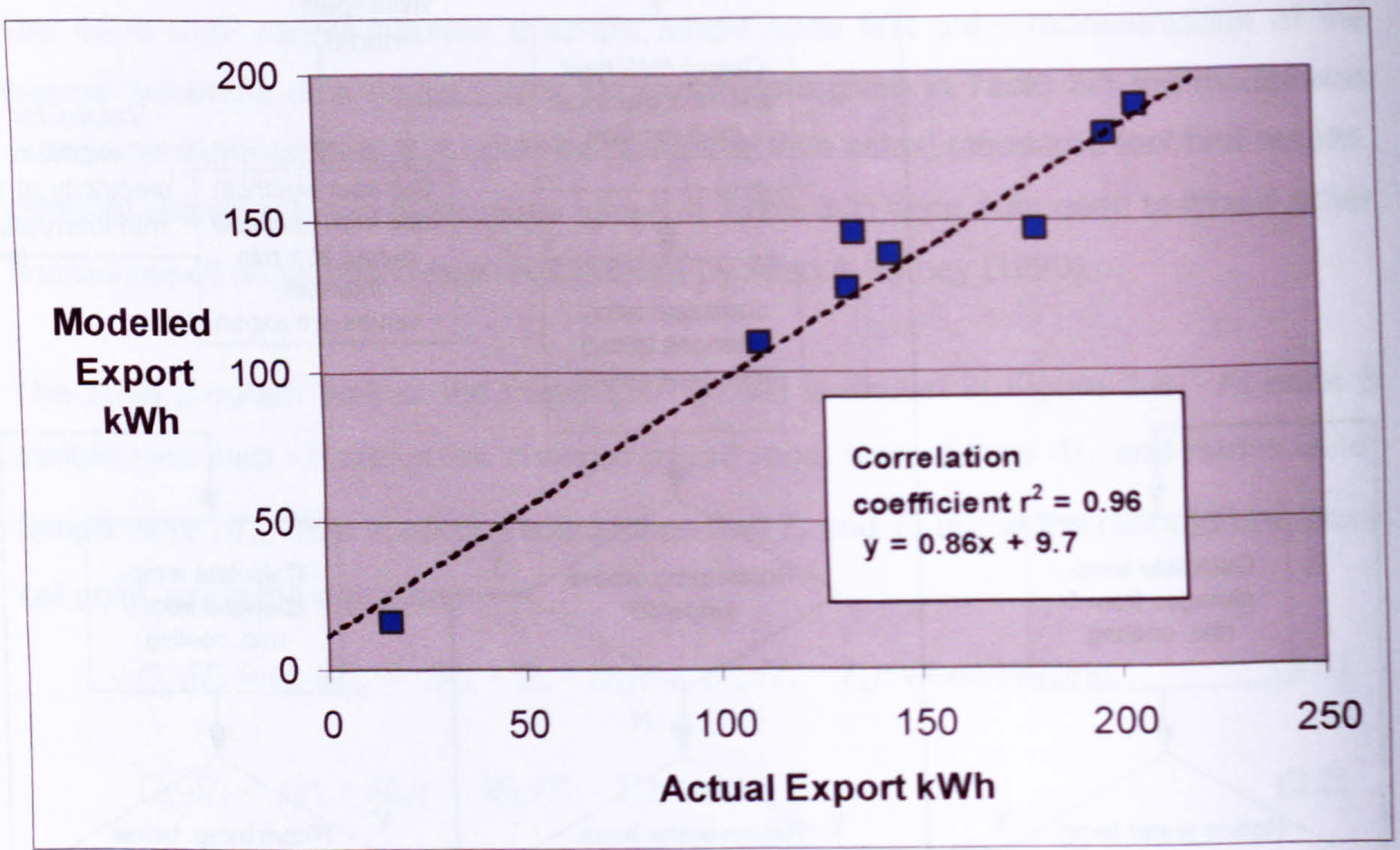

Figure 3-7 Validation of export modelled by month against actual measurements obtained from the test bed

Six modelling studies were conducted using combinations of three different house types and two distinct occupancy and appliance scenarios over a heating season. The set of house types comprised a detached house (similar to, but larger than, the test house), a modern semi-detached house, and an older terraced house. Their floor areas and assumed thermal properties are given in Table 3-2; the thermal parameters were calculated using standard thermal transmittance coefficients (U values) and specific heat values from Clarke (2001) for the building materials used. Their size and construction was chosen, from the options offered by Allen & Pinney (1990), to be representative of the 7-8 million larger owner occupied houses in the UK identified by Crozier-Cole & Jones (2002) that can be satisfactorily heated in the UK by a micro CHP device with the level of heat output provided by the unit under test.

Property	Detached	Semi-detached	Terrace
Floor area m^2	150	100	110
Thermal capacity kWh / °C	17	8	12
Steady state thermal load W / °C	420	350	250

Table 3-2 Size and thermal properties of modelled houses

The occupancy scenarios were:

- Low. 2 people both out of the house between 09:00 and 17:00 weekdays but at home all day weekends, with a gas hob and oven, a washing machine but no tumble drier, a fridge and separate freezer, and typical usage of small appliances.
- High: 4 people with some occupation at all times, and, in addition to the electrical appliances in the Low model, an electric hob and oven, and a tumble drier.

Hourly external ambient temperatures for the modelling were drawn from the test reference year data for Manchester airport published by CIBSE (2002). A room temperature set point during occupied periods of 21°C was assumed for the main modelling studies; subsequently the effect of different set points was investigated. The results are summarised in Table 3-3, which shows levels of micro CHP output ranging between 2 and 3.4 MWh, and the proportion exported ranging from 37% to 62%. These figures are consistent with the 44% measured for the test bed house, since the latter had variable levels of occupation and appliance use intermediate between the high and low scenarios. They are significantly higher than export levels predicted by previous studies, e.g. 15% (Harrison & Redford, 2001), 33% (DGCG, 2004), 40% (Peacock & Newborough 2005) which relied on modelling that did not include the fine-grained intermittency of domestic electricity consumption. They have been confirmed by export data subsequently published by the Carbon Trust (2007) based on aggregated data from all the micro CHP units (including the test bed unit) participating in their trial, giving an average export level of 49%.

The results from the present research[6] show that for micro CHP to be widely adopted it is essential for the consumer to be offered a fair price for export electricity which reflects

[6] Published in Energy & Buildings (Boait *et al.*, 2006).

the cost of the gas consumed in its production and the investment made. They also show that it will be worthwhile to manage the micro CHP operation and domestic electricity demand as far as possible so that the electrical output is consumed locally, thereby giving the consumer a financial saving equal to the full retail price of the imported electricity that would otherwise be used, and also improving overall efficiency through avoiding the local distribution network energy losses of about 2.5% (Silva & Strbac 2007) that will be incurred by export.

Scenario	**MicroCHP output kWh**	**Proportion of export %**
Detached house, low occupancy	3372	60
Detached house, high occupancy	3265	37
Semi-detached house, low occupancy	3167	62
Semi-detached house, high occupancy	2804	40
Terraced house, low occupancy	2164	61
Terraced house, high occupancy	1760	44

Table 3-3 Micro CHP modelling results

From this investigation two requirements for optimising the management of micro CHP were identified, both relating to the benefit from correlating the electricity generated with domestic electricity demand. Firstly, if a small adjustment is applied to the room temperature set point (by 1 or 2°C) so that it rises during the day, electricity is generated later in the day when demand is higher. Figure 3-8 below, obtained from the modelling study for a terraced house with high occupancy, shows the effect. A temperature set point rising from 20 to 22 °C during the day moves the majority of the generator output to the afternoon resulting in a reduction of 37% in the amount of electricity exported, relative to the export arising with a static temperature set point (21°C).

Secondly, It is important that the time settings which determine when space heating is required align accurately with occupant activity patterns. For example, if heating is started too early in the morning peak electricity generation will occur before the early morning electricity demand created by electric kettles, lighting, etc. Evidence was presented in Chapter 2 (e.g. Critchley 2006) that a significant and vulnerable proportion of the population have difficulty in setting heating controls accurately or at all. Also the change to and from summer time introduces dislocations in time settings which few existing controls can handle automatically. The modelling studies showed that for low occupancy households a misalignment in time settings by 1 hour increased export levels by 5%. So a mechanism for automatically determining time settings would improve efficiency and the financial return to the consumer, and be helpful to those who have difficulty with time settings.

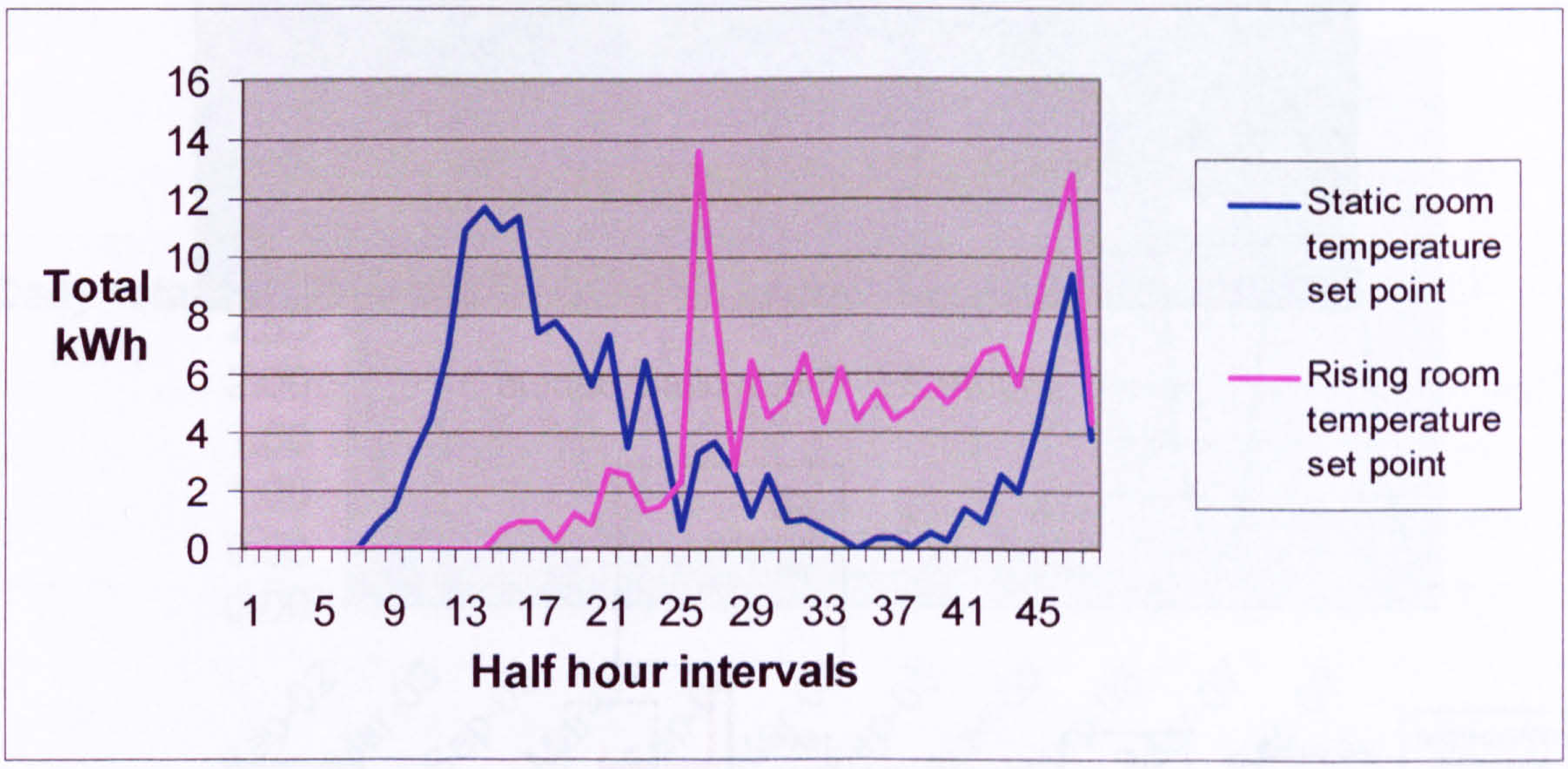

Figure 3-8 Aggregate micro CHP generator output in each half hour interval during October for a terraced house with high occupancy.

These requirements are carried forward to Chapter 4 where they are included in the compilation of desirable functions of a domestic energy management system.

3.4 Photovoltaic Generator

A photovoltaic (PV) generator is installed on the kitchen roof as shown in Figure 3-9 - the picture was taken prior to installation of the solar thermal panels. It comprises a set of 9 BP Solar SX 210S polycrystalline silicon panels with a total peak DC output under reference conditions (solar illumination of $1kW/m^2$ and ambient temperature of 25 °C) of 1.08 kW. The DC output is coupled to the AC mains via an SMA SB-850 inverter with a nominal peak AC output of 850W. This under-rating of the inverter ensures optimum efficiency for UK patterns of solar irradiation. The wiring schematic in Figure 3-10 shows how compliance was achieved with the small embedded generator installation standard G83/1 (ENA 2003) for both the PV and micro CHP generators.

Figure 3-9 Photovoltaic panels

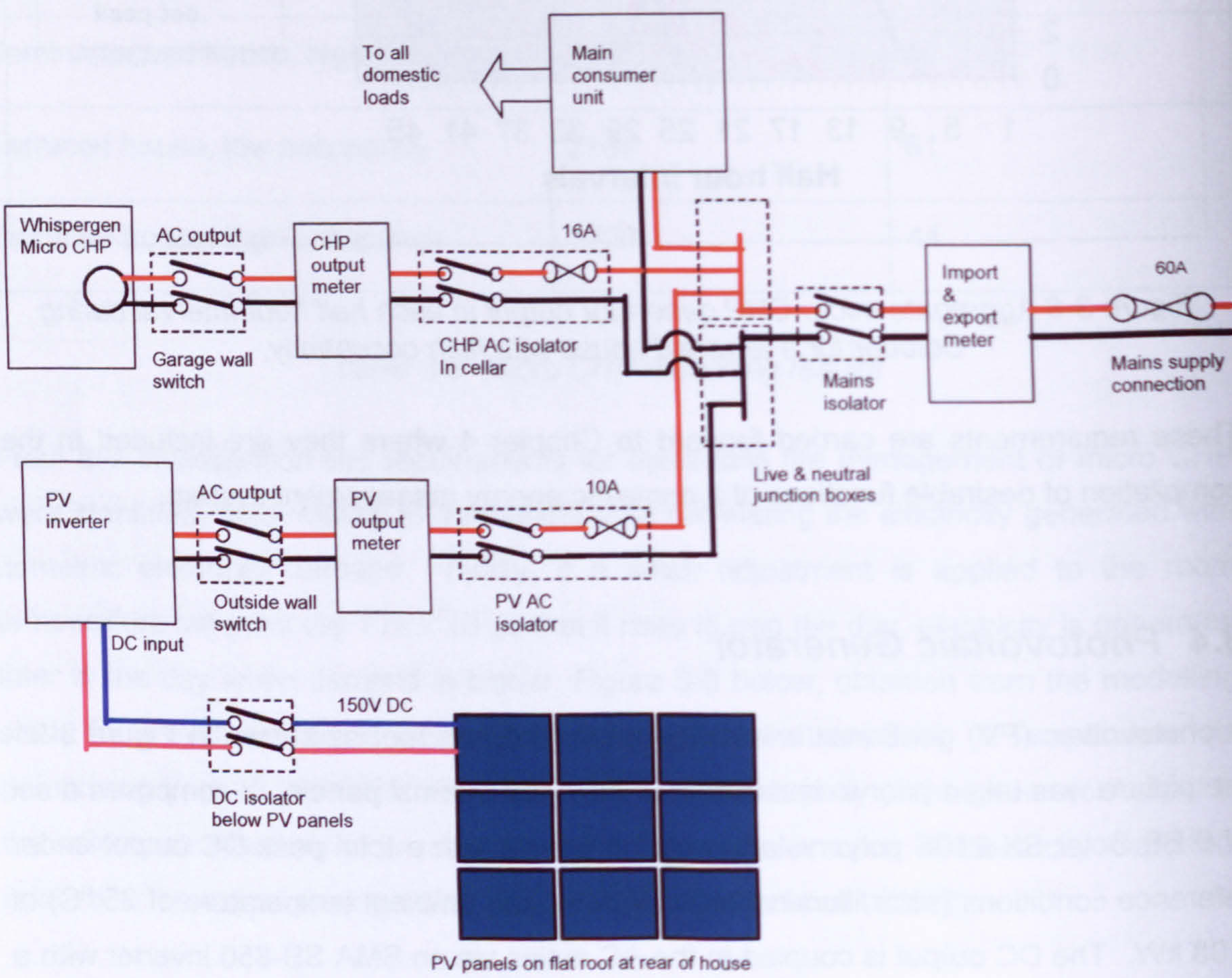

Figure 3-10 Test bed electrical wiring schematic

The output achieved from this generator since installation in June 2002 is shown in Figure 3-11 below, in the form of daily output in kWh averaged by month and by year.

Annual figures are a rolling average with an interesting profile – it rises to an initial peak in December 2003 due to the cumulative effect of the outstandingly sunny weather in 2003. It then falls away to a more typical average, which also reflects the slight reduction in output due to the ageing effect expected for polycrystalline PV panels in the first year of operation. From then on there is a slight rising trend. The rolling averages correspond to annual energy outputs in the range 804-930 kWh.

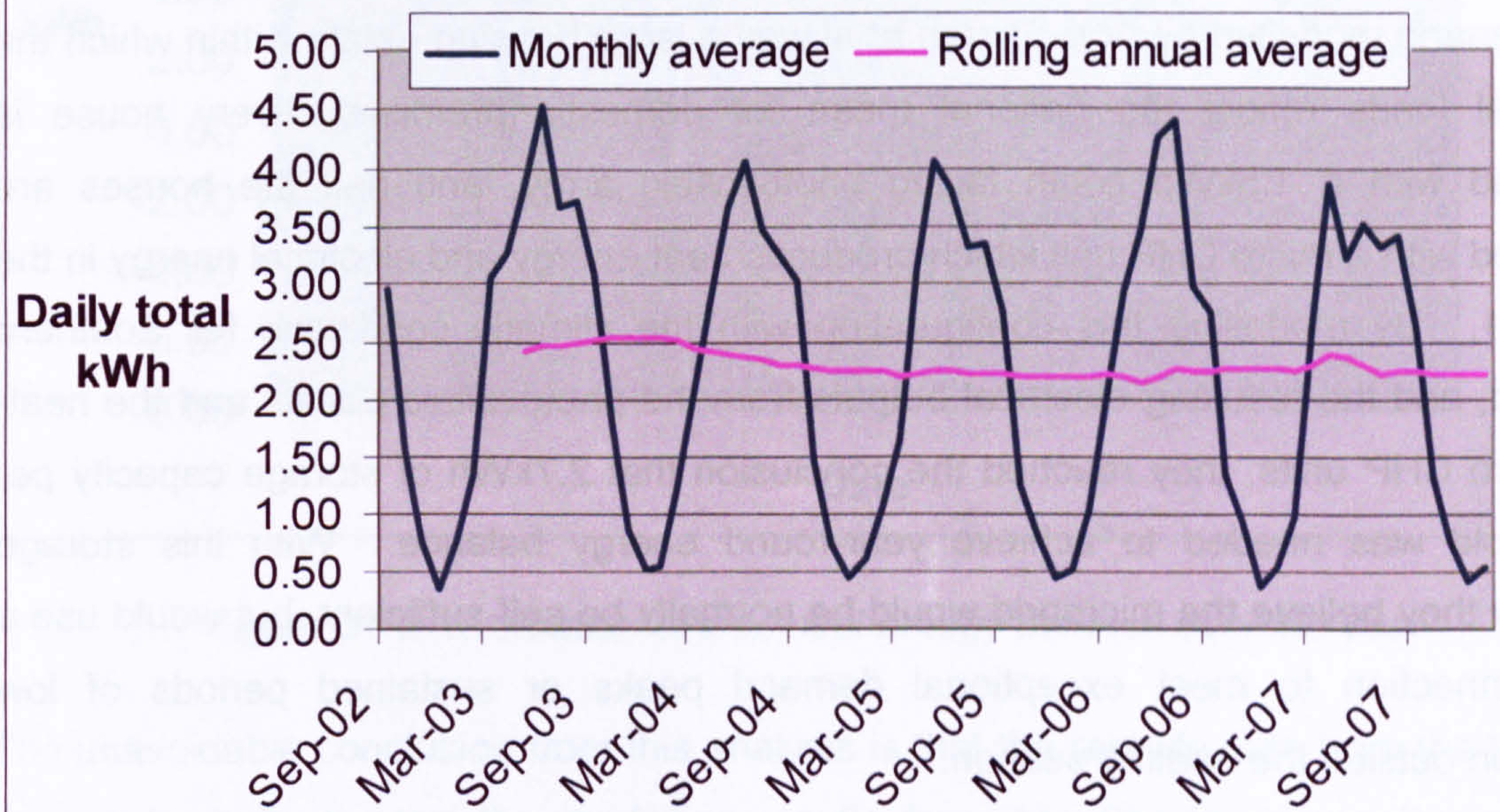

Figure 3-11 Photovoltaic generator output

The investigation of management requirements for PV has focussed on the interaction and synergy between PV and micro CHP. The first requirement identified is the metering issue that arises when PV is installed in the same house or building as micro CHP. Because the PV output attracts Renewable Obligation Certificates (ROCs) currently worth £45/MWh in addition to the basic value of the electricity generated, it is more valuable than the CHP output. ROCs also accrue for output consumed locally, whereas payment is normally only made for export electricity from micro CHP. However, metering each device separately and communicating the results to a data collection point is likely to be cumbersome and expensive relative to the value of electricity generated. It would be preferable to be able to discriminate between electricity generated by PV (and any other renewable source such as wind that attracts ROCs) at a single measurement point. This requirement is carried forward to Chapter 4 where a solution is proposed.

As discussed in Chapter 2, the proposition by Abu-Sharkh *et al* (2006) that a microgrid based on domestic PV and micro CHP could be viable with a limited amount of storage presented an opportunity to extend their research using real-life data from the test bed. Also, experience from operation of the micro CHP showed that some of the storage might be provided from the thermal capacity of the building rather than in the form of a battery. The task of testing the Abu-Sharkh findings was undertaken as an MSc dissertation (Eckford 2007).

The scenario modelled by Abu-Sharkh *et al* was a large housing estate within which the electrical loads reflect the national mean for domestic premises, every house is equipped with a 1.5kWp south facing photovoltaic array, and half the houses are equipped with a micro CHP unit which produces heat energy and electrical energy in the ratio 3:1. By modelling this configuration with the climatic conditions for Southern England, and the resulting electrical outputs from the photovoltaic panels and the heat-led micro CHP units, they reached the conclusion that 2.7kWh of storage capacity per household was needed to achieve year-round energy balance. With this storage capacity they believe the microgrid would be normally be self-sufficient, but would use a grid connection to meet exceptional demand peaks or sustained periods of low insolation outside the heating season.

To test this hypothesis the data from the test bed for 2005 was analysed. Because the test bed PV installation is 1kWp, the micro CHP has a heat/electricity output ratio of 8:1, and the electrical load is higher than the national average, it was necessary to multiply each of the test bed data sets by a constant scaling factor (e.g. 1.5 for the PV data) so that it matched the scenario postulated by Abu-Sharkh *et al.* The resulting energy balance was calculated over the year, and is plotted in Figure 3-12 in the form of a rolling mean of the net daily electrical energy balance (i.e the daily net import or export to the grid from the house). The rolling mean is calculated over 5 days, to reflect the smoothing effect of the proposed storage, and the averaging of electrical load variations between one house and another that would occur in the scenario.

The results are very interesting – it is clear that from the beginning of November through to the end of May (i.e. the heating season) there is generally a healthy positive net balance, and the only deficits arise during short periods of warm weather or when exceptional loads occur such as Christmas. However, from mid-July through to late September there is a continuous deficit. Examination of the data shows this is due to inadequate output from the PV panels to meet demand, at a time when the weather is too warm for space heating so micro CHP generation is limited to that arising from production of domestic hot water.

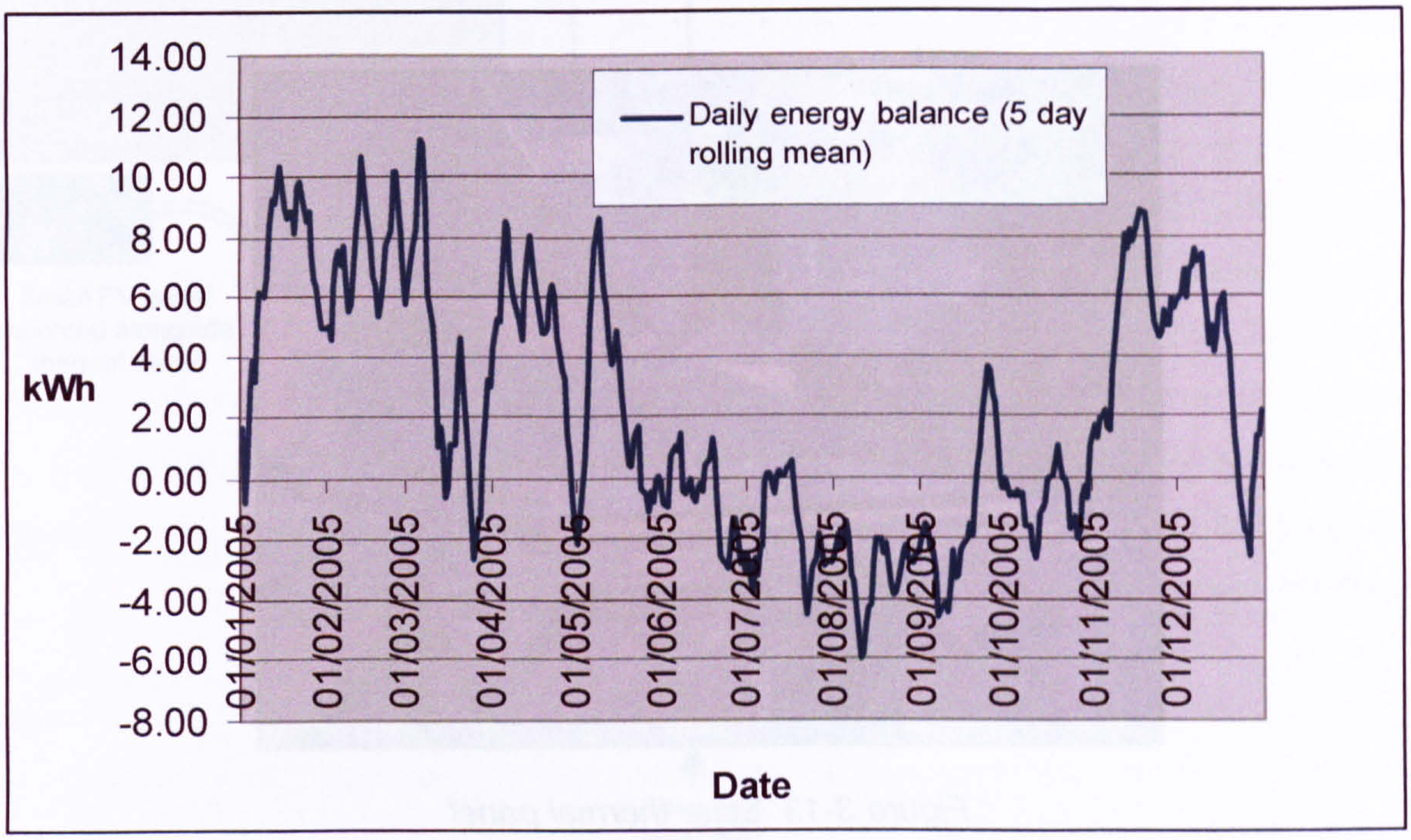

Figure 3-12 Evaluation of electrical energy balance over the year

The unavoidable conclusion from this analysis is that the real-life data from the test bed does not wholly support the modelling results from Abu-Sharkh *et al.* Because the outputs from all the PV panels on a microgrid will be correlated, the only way in which the late summer deficit can be addressed is by increasing the PV panel size. The test bed data indicate that an increase in PV output per dwelling to about 3kWp would be needed to limit deficits to periods of low insolation. The implications of these results for the feasibility of this form of microgrid are discussed in Chapter 5.

3.5 Solar Thermal System

A solar thermal panel with an area of 2.8 m^2 is installed at the front of the kitchen roof as shown in Figure 3-13 (the panel with the large insulated pipes emerging on the right). It is manufactured by Solartwin Ltd, and was chosen for two attributes: it is frost proof so needs no anti-freeze or draining down in winter, and uses a PV – powered pump to circulate the hot water generated to the hot water cylinder so requires no mains power. A schematic diagram of the plumbing circuit is shown in Figure 3-14. Because the pumping rate is proportional to the incident solar energy the temperature differential between input and output is maintained through the variations in solar flux typical of the

UK climate. To ensure a useful temperature rise at low levels of solar radiation the pumping rate can be quite small, just a few millilitres per second. A detailed justification of these design features is provided by Grassie *et al* (2002).

Figure 3-13 Solar thermal panel

The performance of the solar thermal panel is measured using a flow meter installed in series with the panel, and temperature sensors on the flow and return pipes giving the temperature rise achieved by the panel. The solar heat power H_s captured at any given time is then given (in Watts) by:

$$H_s = 4.2F(T_h - T_c) \tag{3.4}$$

where F is the flow rate in millilitres per second, T_c is the flow (cool) side water temperature, and T_h is the return (hot) side water temperature. This method of power measurement is only accurate as an instantaneous value as long as the input temperature is constant. If the input temperature falls, for example due to hot water being drawn off, then it will take up to 30 minutes for that fall to be reflected in the output temperature because of the volume of water (about 3 litres) in transit through the system and the low flow rate (between 0.1 and 0.6 litres per minute at useful levels of thermal output). So there will be a short term rise in the apparent power output. This effect will of course be reversed as the input temperature recovers. However, when integrated over time the power values will give an accurate figure for the energy captured.

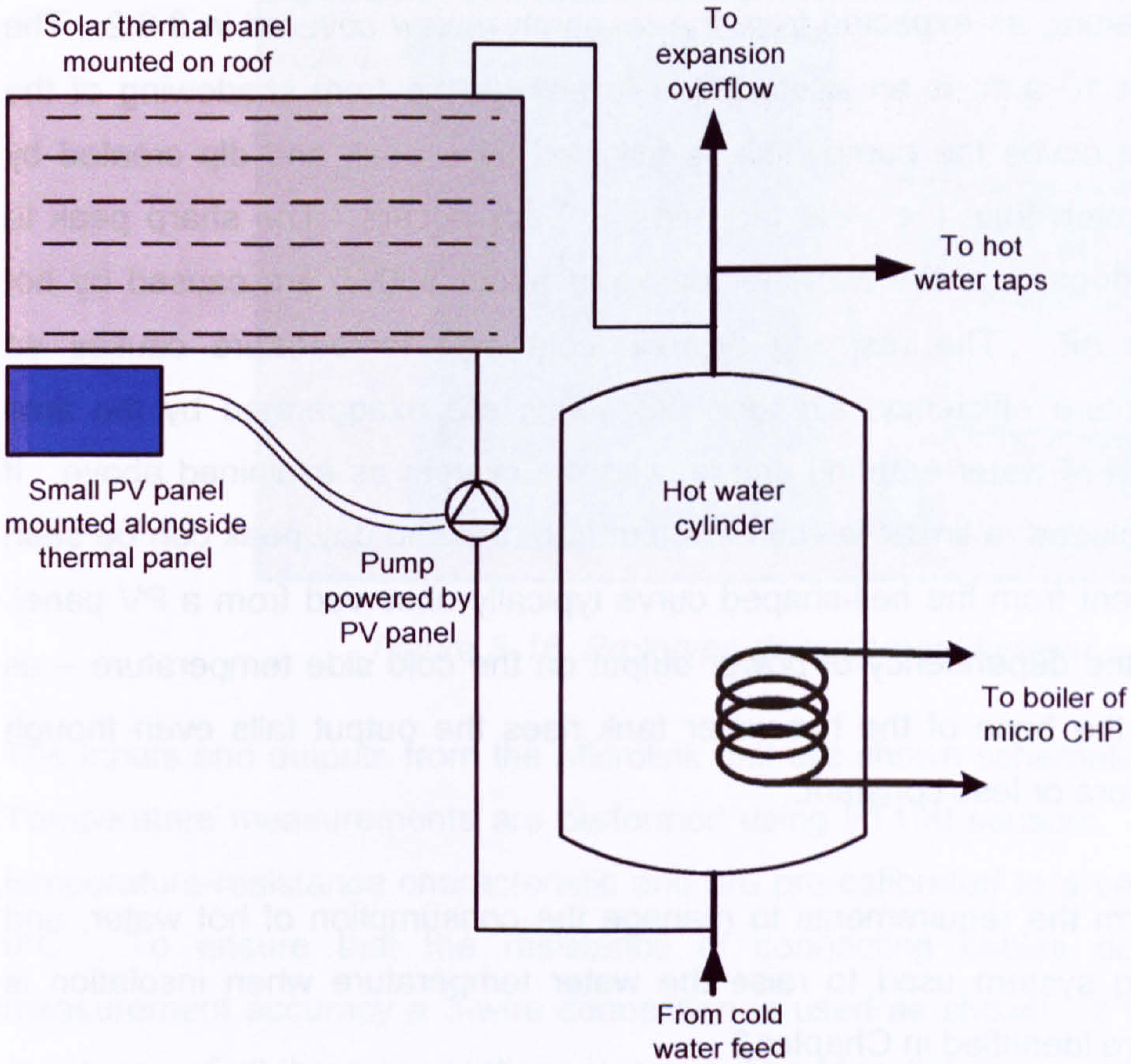

Figure 3-14 Schematic of solar thermal system

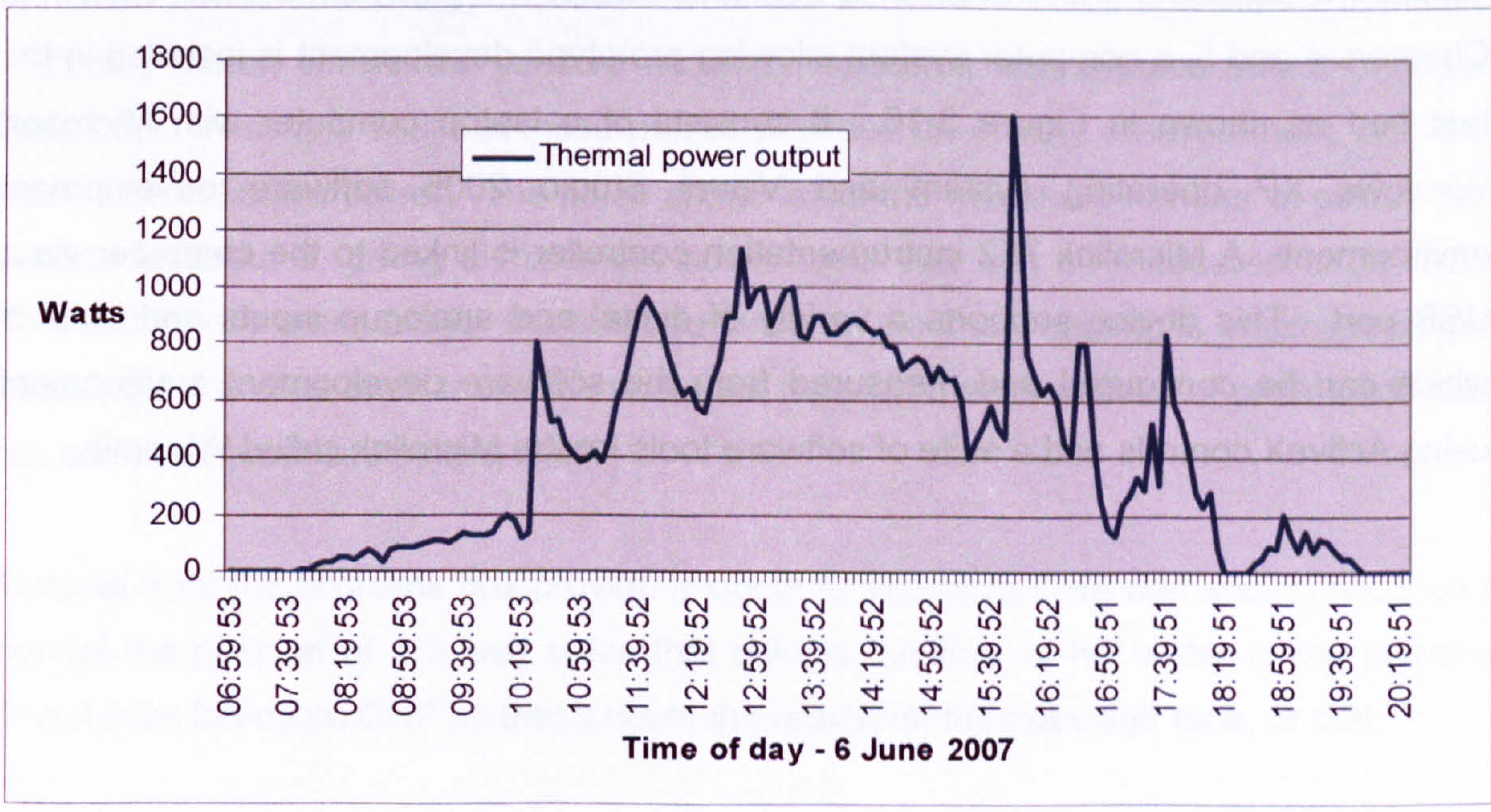

Figure 3-15 Power output of solar thermal system

A typical output profile for a sunny day is shown in Figure 3-15. It confirms the dependency of the energy output of a solar thermal panel on the hot water usage pattern and temperature, as expected from the research review covered in 2.6.2. The initial peak at about 10 a.m. is an artefact due to emergence from shadowing of the small PV panel that drives the pump. This is followed by a peak and dip created by intermittent cloud cover, then the expected mid-day peak occurs. The sharp peak to 1600W in mid-afternoon, and the two later peaks at about 800W, are caused by hot water being drawn off. The resulting drop in cold side temperature causes an improvement in capture efficiency, although the peaks are exaggerated by the time delay between a unit of water entering and leaving the system as explained above. If these peaks are excluded, a linear fall-off of output from the mid day peak can be seen which is quite different from the bell-shaped curve typically observed from a PV panel. This again reflects the dependency of power output on the cold side temperature – as the temperature at the base of the hot water tank rises the output falls even though insolation may be more or less constant.

These results confirm the requirements to manage the consumption of hot water, and the auxiliary heating system used to raise the water temperature when insolation is inadequate, that were identified in Chapter 2.

3.6 Energy Management System Prototype

To test the concepts and design for a domestic energy management system set out in Chapters 4 and 5, a computer system allowing prototype development is installed in the test bed as shown in Figure 3-16. It consists of a laptop computer with Microsoft Windows XP operating system and Visual Studio 2005 software development environment. A Microlink 752 instrumentation controller is linked to the computer via a USB port. This device supports a variety of digital and analogue inputs and outputs which can be configured and measured from the software development environment using ActiveX controls and a suite of software tools for the Microlink called Windmill.

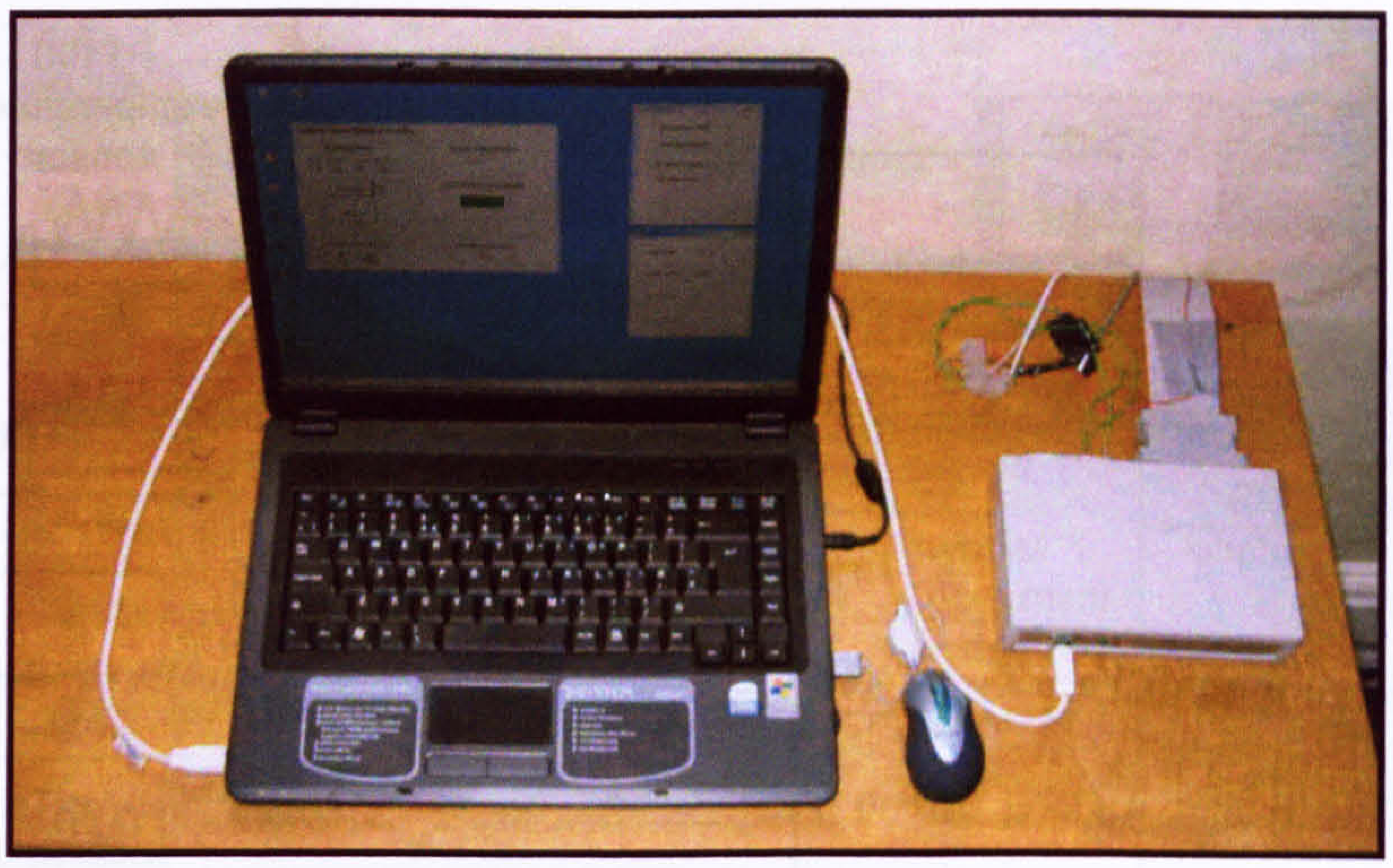

Figure 3-16 Prototype development system

The inputs and outputs from the Microlink unit are shown schematically in Figure 3-17. Temperature measurements are performed using PT100 sensors. These have a linear temperature-resistance characteristic and are pre-calibrated to a value of 100 Ohms at 0°C. To ensure that the resistance of connecting cables does not impair the measurement accuracy a 3-wire connection is used as shown. It is assumed that the resistance of all three connections is equal. The Microlink then subtracts the resistance of the pair of wires connected together at one end of the sensor from the measured resistance across the sensor leads, to obtain the actual resistance of the sensor.

Electrical power and energy measurements are performed using a standard domestic electricity meter, which has certified accuracy, specified with a pulse output of 1 per Watt-hour. A simple count of these pulses provides an energy measurement, and the pulse rate indicates power. The pulse shape limits the maximum number of pulses per second to about 9, giving a maximum power level that can be measured of 32.4kW. This is normally adequate for the test bed since no electrical heating is employed in the house, but care has been taken to ensure the measurement accuracy of peak loads has not been compromised by this limit.

Outputs from the Microlink box provide a signal to the micro CHP demanding heat, and control the position of a 3 way valve that selects the flow of hot water in the primary circuit from the micro CHP so that it heats the radiators, the hot water tank, or both.

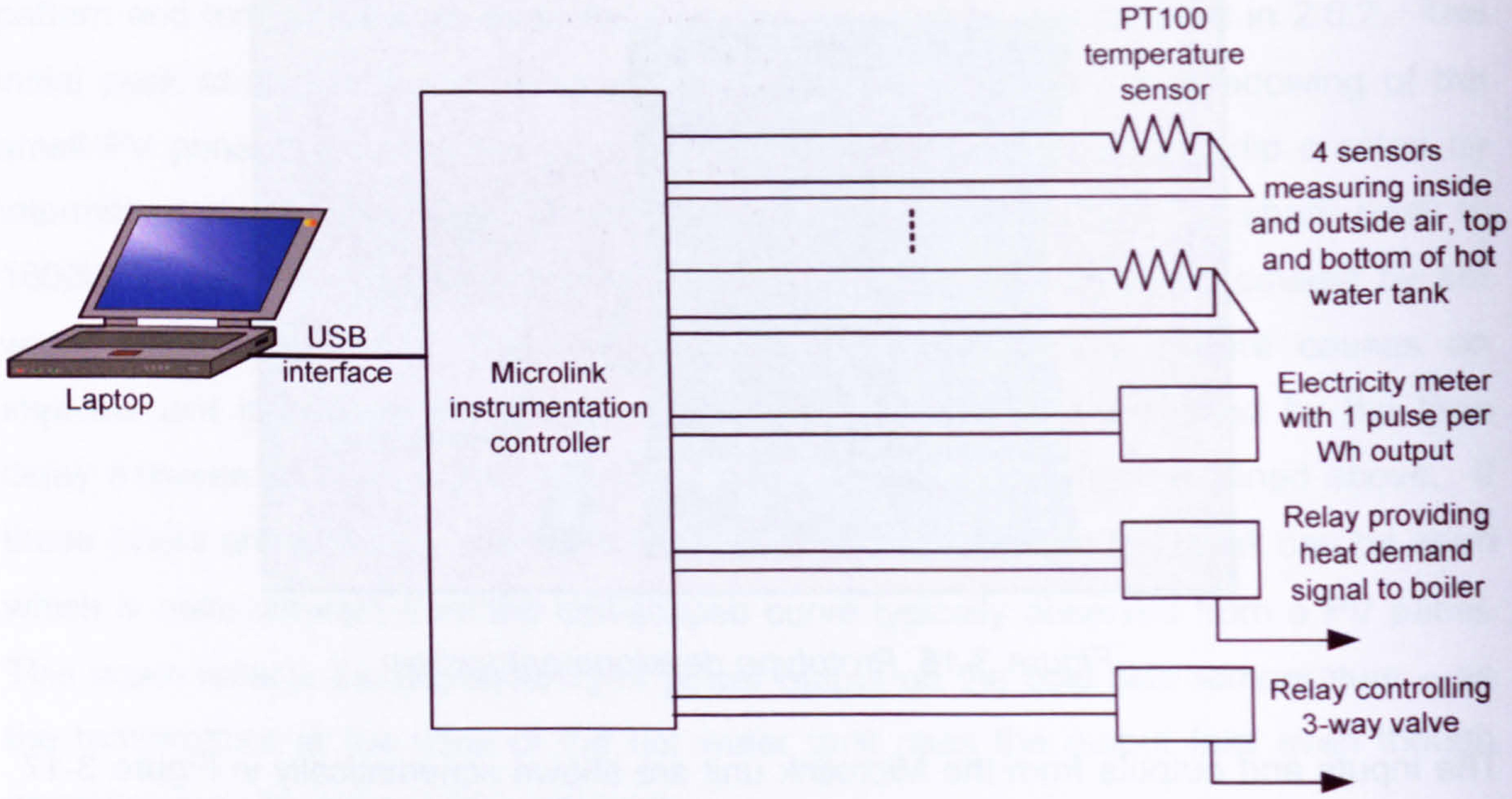

Figure 3-17 Schematic diagram of prototype development system

3.7 Overall Effect on Carbon Emissions

Since the public policy goal motivating this research and the various technologies evaluated in the test bed is reduction of carbon emissions, it is useful to assess just how effective they are in practice. Figure 3-18 shows the annual carbon emissions of the test bed house over 8 years, with the timing highlighted for the major interventions that have been made in its energy flows. The emission levels are calculated from consumption of natural gas and mains electricity, offset by carbon reductions from substitution of grid electricity by low or zero carbon exports. Household motor vehicles are not included. Overall a reduction of 48% on the 2000 level has been achieved.

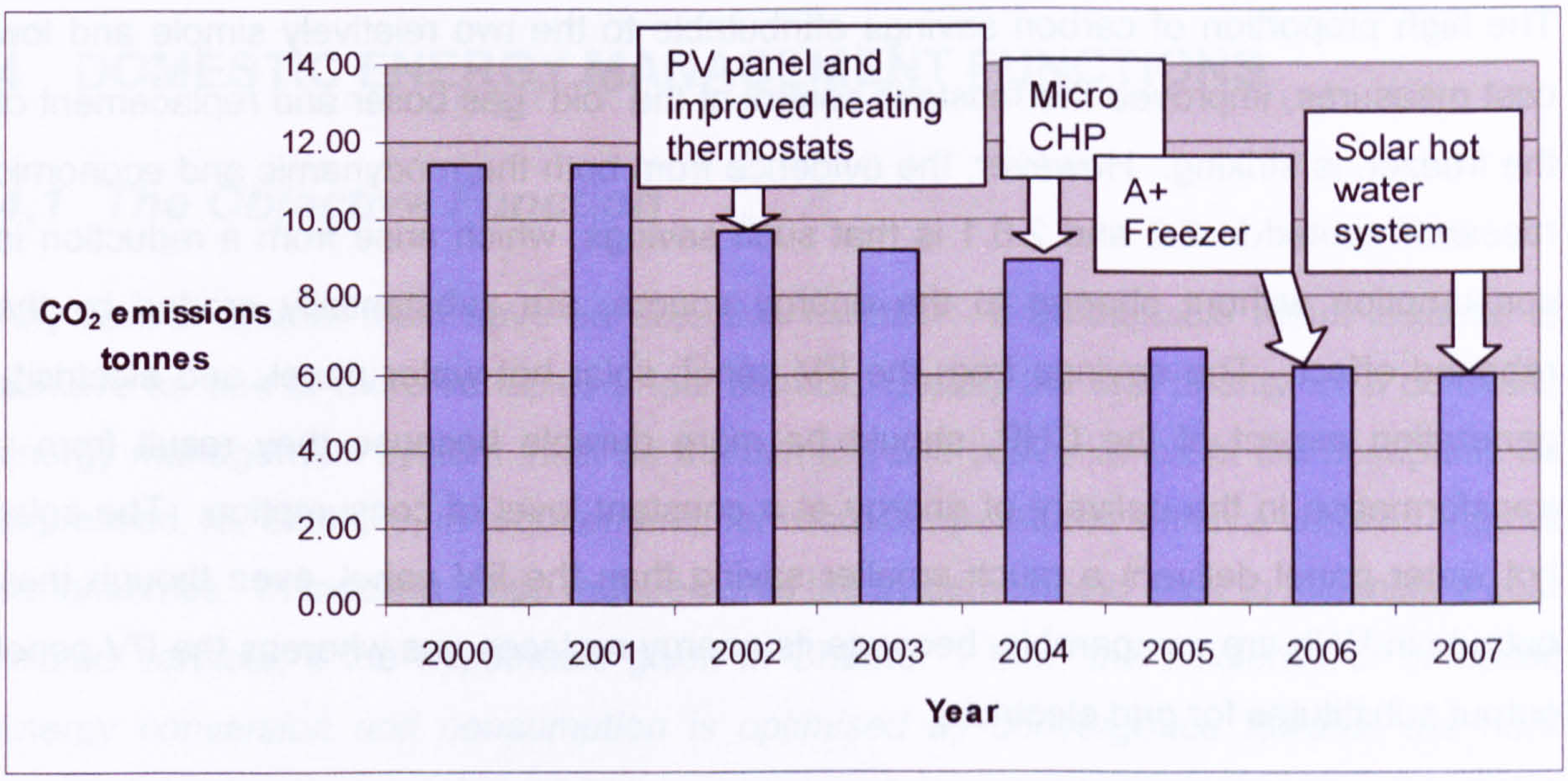

Figure 3-18 Annual carbon emissions of test bed house

Table 3-4 shows the level of reduction in carbon emissions from the 2000/2001 level attributable to each intervention, including some that were essentially good housekeeping (such as purchasing an A+ rated freezer) so have not featured previously in this thesis. Note the calculation of these figures did not take account of variations in aggregate heating demand and occupancy from one year to the next, which from historic data before 2000 can cause up to +/-10% variation in carbon emissions with an unchanged set of energy conversion devices. However the table provides a rough indication of the relative effectiveness of the different technologies employed. Carbon intensities of 0.17kg CO_2 per kWh for gas, and 0.47kg CO_2 per kWh for mains electricity were assumed.

Intervention	Reduction in annual CO_2 emissions from 2001 baseline (tonnes)	Reduction expressed as % of total reduction
Improved thermostatic control of existing non-condensing gas boiler and radiators	1.7	32%
Photovoltaic panel installation	0.4	7%
Replacement of non-condensing gas boiler with micro CHP	2.7	50%
Replacement of freezer with an A+ rated device	0.5	9%
Solar hot water panel installation	0.1	2%

Table 3-4 Reduction in carbon emissions from each intervention

The high proportion of carbon savings attributable to the two relatively simple and low cost measures, improved thermostatic control of the "old" gas boiler and replacement of the freezer, is striking. However, the evidence from both thermodynamic and economic research quoted in 2.2 and 2.6.1 is that such savings, which arise from a reduction in consumption without change to the energy source, are substantially eroded by the rebound effect. The savings from the PV panel, solar hot water panel, and electricity generating aspect of the CHP, should be more durable because they result from a transformation in the delivery of energy at a constant level of consumption. The solar hot water panel delivers a much smaller saving than the PV panel, even though their outputs in kWh are comparable, because its energy replaces gas whereas the PV panel output substitutes for grid electricity.

4 DOMESTIC ENERGY MANAGEMENT FUNCTIONS

4.1 The Objective Function

Any control system must have an objective function - a quantifiable result it seeks to achieve for one or more variables under control. Clearly the first priority for a domestic energy management system must be the comfort and convenience of the occupants as expressed, for example, in requirements for room temperatures within a certain range at certain times. In meeting these requirements the system should seek to minimise a cost related variable; if the hypothesis given in Chapter 1 that "*the efficiency of domestic energy conversion and consumption is optimised by convergence towards the non-equilibrium thermodynamics of living organisms*" is upheld, then the choice of this variable must be consistent with it.

In 2.2 it has been shown that for ecosystems the cost that is minimised should be exergy loss. To test the hypothesis, in the first half of this chapter a comparison is performed comparing exergy loss with two other leading candidates as an optimisation metric. The first, monetary cost, was chosen because it is the default metric for a system operating in a free market for energy, and is being used for this purpose by other research teams in this field as discussed in 2.6. The second, carbon emissions, was chosen because their minimisation is necessarily a dominant policy objective as reviewed in 2.3, which must be translated into practical action at the domestic level. The argument for the hypothesis, which has been drawn from literature review and practical experiment, is set out in five stages in the following sections 4.2- 4.6. In summary, the steps covered in each of these sections are:

- the need for domestic energy management decisions to be decentralised is justified;
- the nature of the complex aggregate system that will be created when millions of interacting autonomous domestic energy management systems with the same objective function are instantiated, is examined;
- minimisation of carbon emissions, while pre-eminent as a policy goal at global level, is shown to be impractical as an objective function at domestic level;
- exergy loss is shown to be preferable to monetary cost, for theoretical reasons drawn from both physical and social science, and also for reasons of engineering practicality;

- minimisation of exergy loss is shown to provide satisfactory outcomes with respect to reducing both monetary cost and carbon emissions.

With this conclusion as a basis for the objective function, the practical information flows and control methods required by a domestic energy management system that can satisfy all the requirements brought forward from Chapters 2 and 3, and thereby address the aims of the project, are investigated in the second half of the chapter.

4.2 Primacy of Decentralised Decisions

An assumption so far hidden in the premise of this work is that a domestic energy management system should be locally autonomous, in that most or all of the decisions it makes are taken and executed within the curtilage of the home, although they will naturally be influenced by information from outside such as energy tariffs. Alternative centralised control models do exist - the radio teleswitch system (BSI,1993) currently issues commands into about 200,000 homes which switch electrically heated thermal storage radiators on and off. However, the locally autonomous model is seen as the only viable approach for the majority of control functions for a 21st century home in Britain, for two major reasons.

Firstly, there is a deep cultural preference for a self-contained home with a visible perimeter and its own facilities. Anyone returning to England on a flight from Europe cannot fail to observe the contrast between the flats and apartments that are the dominant form of dwelling in the European city they have just left, and the square miles of little houses and tiny gardens that form English suburbia. This is reflected in the scarcity of district heating schemes in the UK and the difficulties experienced in deploying community CHP installations. So even if central control was attractive for technical reasons, it would be resisted as alien to the established order. It is not surprising that the majority of radio teleswitch installations are in social housing and the numbers in use are declining (Kema, 2005).

Secondly, because the majority of these houses are owned by the occupants, they make their own decisions on the choice of energy converting and consuming appliances within it. These decisions will in future cover a far wider range of devices (such as air conditioning units, solar thermal panels, and micro CHP units) as the pressures of climate change grow, and will be made on the basis of the financial and physical constraints and preferences of the individual. The thermal properties of adjacent and superficially identical houses are also often very different because one home owner may have chosen to install double glazing and cavity wall insulation while his neighbour has not. So each home will effectively be unique in the way that the appliances within it interact with each other, with the thermal properties of the home and with the behaviour patterns of the occupants. This diversity arising from consumer freedom will ensure that, as long as there is a competitive market for the supply of energy, it will be very difficult for an energy supplier to obtain the efficiencies of scale that would make centralised decision-taking a worthwhile option in engineering or economic terms.

So the domestic energy management system envisaged by this thesis will take most of its decisions locally, based on information from sources both internal and external to the home. It is recognised that there are some specific scenarios relating to electrical safety or security of supply where responding to a centrally generated command would be necessary. For example, where there is sufficient microgeneration in a locality to permit island operation, it may be necessary to force a temporary shut down of all generators to allow repair work on the distribution network to be performed safely. The system design must admit this form of overriding command, but on a day to day basis the homeowner will expect his appliances to give priority to his needs.

This principle of decentralising decision taking as far as possible has been recognised and accepted by other researchers in this field, such as Nestle *et al* (2007) and Warmer *et al* (2007). Both teams are seeking to realise the "virtual power plant" concept in Germany and Netherlands respectively, under the EU "Smart Grids" programme. This concept envisages co-ordination of large numbers of micro generators so that they appear to the grid in some sense like a large conventional generating plant. So they have reached this conclusion on decentralisation despite the initial top-down premise of their work.

4.3 Properties of the Aggregate System

However, while this local control system autonomy may be inevitable, it opens up a difficult issue when the behaviour of a very large number of such systems is considered. Because each domestic system will be able to exchange energy with the local electricity distribution system, and will influence and respond to energy markets, they will interact with each other. Where homes are in physical contact, such as an apartment block or terraced street, there will be thermal interaction between them. So the behaviour of these locally autonomous systems, each responding to different circumstances driven by consumer freedom as outlined above, must be considered in aggregate.

Because it is impossible to exhaustively compute all possible outcomes, predicting the behaviour of such an aggregate involves looking for the emergent properties of a complex system, a class of problem that is often intractable. As discussed in Chapter 2, the laws of thermodynamics predict accurately the emergent properties of an aggregate of molecules moving randomly in a fluid when that fluid is at or close to equilibrium, but they are unable to predict the emergent behaviour of a non-equilibrium system. A large aggregation of energy consuming households is far from equilibrium in many of its thermodynamic attributes.

A simple example of an undesirable emergent phenomenon is the "TV pickup" seen on the current grid system, when a break in a popular TV program triggers a very rapid rise in electrical load caused by viewers switching on their electric kettles. This is an emergent event arising from the interaction of human behaviour with two complex systems, the broadcast media and the grid. A similar issue would arise if a large number of micro generators increased their export to the grid within a short period of time - the resulting transient could lead to instability or loss of service through tripping. The more subtle dangers that lie in emergent properties of a complex information system that is affected by human behaviour are illustrated by the Internet. When its precursor the Arpanet was conceived and constructed as a telecommunications network that could withstand nuclear warfare through its topological richness, none of the higher level phenomena seen today, such as virus propagation and the World Wide Web, were predicted. Computer viruses and other forms of malware have of course their origins in society as well as in system engineering, but the aggregate system under consideration here will also be exposed to the full range of human behaviour so must be resistant to deliberate attempts to disrupt it.

There is no established methodology by which emergent phenomena can be predicted. Morowitz (2002) argues (in the context of complex thermodynamic systems) that Popperian science requires exhaustive evaluation of all states of the complex system and "introducing selection algorithms to look for plausible solutions is an epistemological approach that is much more difficult to evaluate by falsification, and it is too easy to be impressed by metaphoric verification". He proposes that science can proceed by applying pruning rules that limit the space of possible solutions. For an engineering problem, if the predictions from analysis are to be at all useful, these pruning rules must be implemented as constraints within the operational system limiting the range of states it can occupy.

The objective function of an autonomous domestic energy management system must therefore embody pruning rules that constrain the behaviour of the aggregated system to give benign and stochastically predictable outcomes. Many authors, e.g. Boait (2002), have drawn an analogy between distributed energy systems and the internet. The risks implied by this model must be considered as well as the benefits.

4.4 Minimisation of Carbon Emissions

The economic benefit of stabilising CO_2 levels below 550ppm is now clear (Stern 2007). As this goal implies ultimate reduction of CO_2 emissions to 80% below current levels the policy and economic pressures on every energy consuming system to minimise CO_2 emissions can be expected to intensify. However the question here is whether this forms a suitable objective function for a domestic energy management system. The main argument against it is that as a result of these pressures many energy sources of relevance to the system will have zero carbon content, hence there will be no basis for the energy management system to discriminate between them.

A simple example is a home equipped with photovoltaic panels and a biomass fired boiler. The hot water cylinder can be heated either by the boiler or an immersion heater. To meet hot water demands in summer the energy management system needs to decide whether to use the PV generated electricity or start up the boiler. It cannot discriminate between these sources on the basis of their CO_2 emissions so would need some other parameter, probably related to cost or efficiency.

A similar problem would arise in making use of the CO_2 emissions per kWh from import electricity generation as a controlling metric for demand side management. Table B4 from The Energy White Paper (DTI, 2007) predicts the generation fuel mix for 2020 to be as shown in Table 4-1 below. The scenario from that table which includes new nuclear has been selected since that is the Government's preferred policy.

Fuel Type	Output TWh	% of total
Coal (conventional)	64	18.3
Coal (carbon capture and storage)	13	3.7
Oil	1	0.3
Gas	156	44
Nuclear	33	9.4
Renewables	67	19
Imports	16	4.5
Storage (*sic*)	3	0.8

Table 4-1 Electricity generation fuel mix for 2020 (DTI, 2007)

It can be seen that the carbon-free element is about 32% of the total (comprising coal with carbon capture, nuclear, and renewables). Nuclear and renewable generators will be despatched to meet the base load because of their negligible marginal fuel cost, and carbon capture will tend to be next in the merit order because of its high capital cost and relatively low fuel cost (since it will avoid the costs of carbon emission arising through taxes or cap and trade schemes). So at times of low demand it will be possible for grid electricity to have zero carbon content, particularly when weather conditions cause wind output to surge. The long term collective average capacity factor (i.e. the actual generated output relative to maximum possible output) of all UK wind generators is 30%, but rises to above 60% for about 3% out of the 20% of annual hourly intervals when demand is low (Sinden, 2007).

It could be argued that a secondary objective function be brought into play by the domestic energy management system when CO_2 emissions fail to provide a useful basis for a control process or decision. The objection to this approach is that it is difficult to predict exactly where and when the secondary function will be invoked. This makes the critical requirement from 4.3 - benign behaviour by the aggregate system in all circumstances - difficult to assure. So minimisation of CO_2 emissions is rejected as impractical for an objective function, but it is clearly necessary to show that the chosen function is effective in ensuring domestic energy consumption contributes to the policy goal.

4.5 Minimisation of Monetary Cost

Cost minimisation is the most obvious, and arguably the only possible, overall objective function of an energy management system that will only be adopted on a large scale if it offers economic benefits. Market forces will ensure that the variant of the system that offers the most savings will tend to be the one that is the most popular. Product evolution under competition will therefore ensure convergence on an objective function that delivers the most financial savings to the consumer. This need not necessarily imply that monetary cost (henceforth referred to simply as cost for brevity) must be the metric used to drive the internal processes of the system, since the consumer is only interested in the outcome rather than the internal logic of the system, but it does imply that *a priori* cost is the most plausible candidate and merits close examination.

The use of cost as a controlling metric is already established in electricity generation and distribution. Mature and dynamic markets for electricity, typically operating on a half-hourly time granularity, exist in many countries. Industrial and commercial organisations, whose consumption of electricity is large enough to have access to the wholesale price, use it to control the timing of loads and generators. Nestle (2007) proposes to extend this method to the domestic environment via an intelligent controller which can adjust thermostats on air conditioning and micro CHP. Warmer (2007) takes this a stage further with an ambitious concept for "Power Matcher" software agents which perform auctioneer and bidder functions on behalf of domestic scale electricity consuming and producing devices.

The auctioneer agent works with a group of bidders, probably within multiple dwellings, that is sufficient to provide a viable pool of resources in conjunction with grid import and export handled as two of the bidders. On a cycle time of 15 minutes the bidders indicate their own price elasticity which may be zero e.g. a PV panel will take whatever it can get for its electricity. A device with flexibility such as an air conditioning unit offers a price/demand relationship which depends on how close it is to its set point temperature limits. The auctioneer resolves these bids collectively to determine a local market clearing price as shown in Figure 4-1 (from Warmer, 2007). Q is the energy offered for the next 15 minutes at the given price.

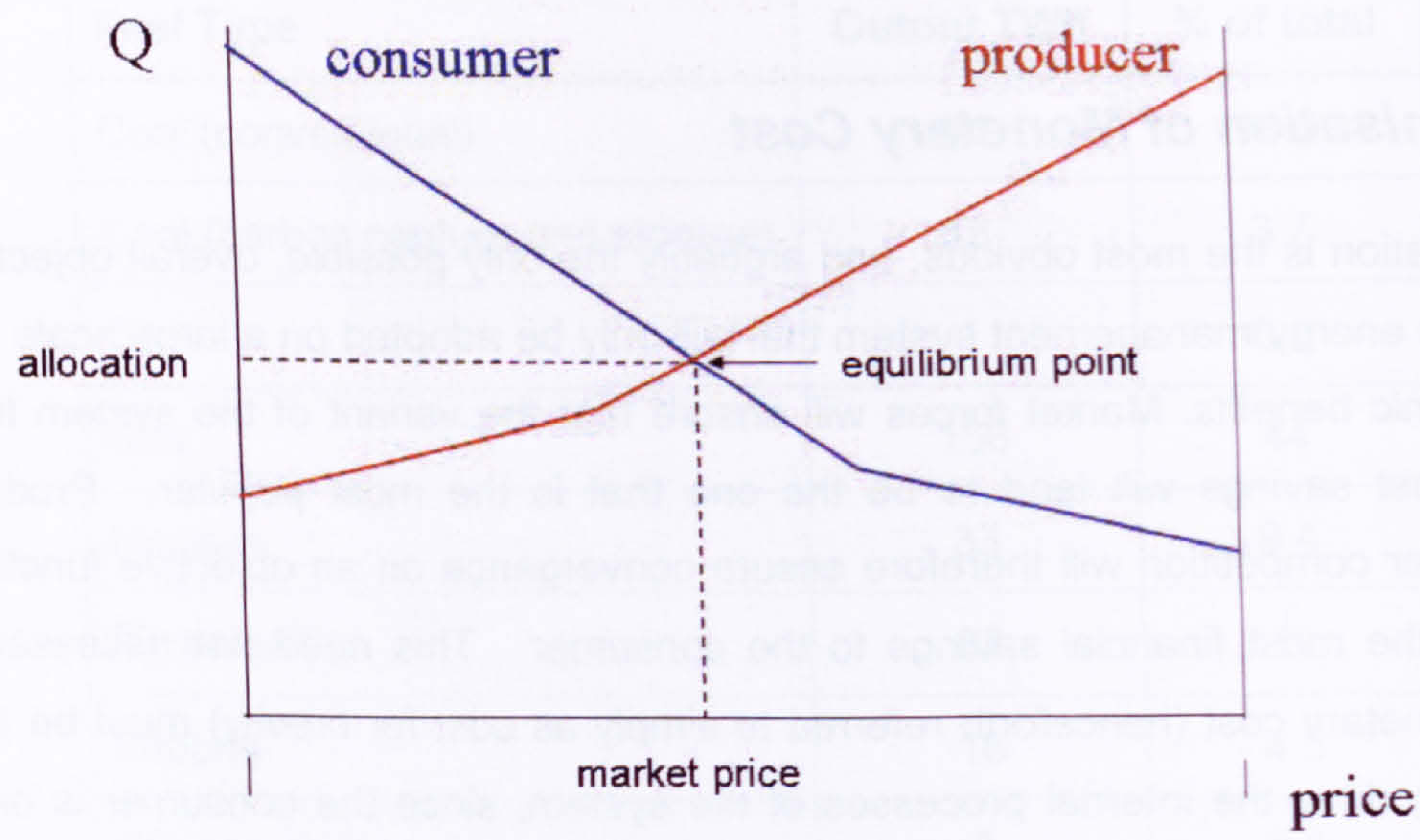

Figure 4-1 Local matching of electricity supply and demand by convergence on a market price (Warmer, 2007)

A local market of this form is the logical conclusion of a cost-oriented approach - it offers an elegant solution to balancing of electrical loads and micro generators at a local scale. However, there are some technical difficulties when applying it to cover all the energy flows associated with a building, not just the electricity:

- The high thermal capacity typical of brick-built homes in the UK[7], which is potentially valuable as an energy store, cannot be exploited efficiently with a 15 minute pricing cycle. A longer time horizon could be built in with some form of futures market but this adds considerable further complexity.
- If the system is managing a set of renewable energy capture devices combined with local electricity or thermal storage, that makes no use of externally market priced sources such as mains electricity or gas, then everything has a zero marginal cost and there is no basis on which to make control decisions. Of course, a secondary objective function could be introduced to cope with this as discussed for CO_2 emissions, with the same objections.

If the energy management within a household is market based then the consumer might reasonably expect the terms of business offered to them by energy suppliers to bear some relationship to the prices paid internally by their system. The implication of this is that the consumer will to some extent be exposed to the dynamics of the wholesale market including the price spikes that occur. Another problem is that the marginal pricing needed to operate the market does not reflect actual economic value – for

[7] By comparison with the timber framed construction common in Europe and North America.

example the electricity from a PV generator attracts ROCs worth about £45 per MWh in addition to whatever the output is worth on a short term basis.

So in practice there is unlikely to be any direct relationship between the cost employed as an objective function and the prices in the consumer's contract with energy suppliers. In fact there are good policy reasons for consumer pricing to have limited dependence on wholesale energy prices. In order to motivate suppliers to invest in energy efficiency an energy service contract is preferable, where the supplier commits to keep the consumer warm for a certain price, which pays for improved insulation and more efficient appliances as well as kWh. The Energy White Paper (2007) sets out the Government's intent to promote this business model with incentives in the Carbon Emission Reduction Target (CERT) that will apply to energy suppliers from 2009 onwards in place of the existing Energy Efficiency Commitment.

The conclusion from this argument is that a domestic energy management system incorporating software agents that are market actors does not empower the consumer to participate beneficially in the wholesale energy market. If the market operated by the system as an objective function has no useful connection with the real life economics experienced by the consumer, and is purely used as an engineering tool, then given its technical disadvantages it seems better to look for a metric that optimally discharges the engineering requirement.

The emergent properties of an aggregate system driven by a financial metric are also a concern. The advocates of this approach hope that the aggregation of these micro markets will simply provide increased liquidity in the existing wholesale markets. This would be fine if these markets were predictable in their behaviour. But there is clearly a risk that political instability caused by climate change and competition for declining fossil fuel resources will drive large variations in wholesale prices, which will feed into the behaviour of the aggregate system leading to undesirable outcomes. For example, if gas prices spike for political reasons while electricity prices remain stable, the cost ratio per kWh between them may fall so low that use of micro CHP is discouraged. This phenomenon, known as low spark spread, has occurred already in the UK for larger scale CHP and has proved a such a major deterrent to its adoption (AEA Technology 2004) that DEFRA is considering proposals for a Government funded hedging scheme to stabilise the spark spread (Ilex Energy Consulting 2005b).

In summary, this thesis argues that because prices are essentially a social construct monetary cost is an unsuitable metric to perform an engineering function. Nonetheless, any alternative must be shown to go with the grain of real markets, since the product implementing it must be capable of succeeding in a competitive market as discussed in the first paragraph of this section.

4.6 Minimisation of Exergy Loss

In Chapter 2 the findings of current research were outlined that show the way in which all physical and biological systems acquire exergy, and seek to optimise its use. Optimisation of exergy use has served to promote ecological richness and evolutionary success among plants and animals for millennia, so the emergent properties from its use as an objective function on a large scale are already visible and are manifestly benign, since otherwise life forms with different motivation would have gained competitive advantage. This option can therefore be justified both from the underlying physics and for its safety as an aggregate system. The flow of the argument in this section is to show that it is also practical and satisfies the cost and carbon emission criteria discussed previously.

For a domestic energy management system the exergy capture itself is a given, determined by the energy conversion devices that are installed in the household, and the mains connections and associated contracts between the householder and energy supply companies. So the resultant objective function of the system is to minimise exergy loss in meeting the consumer's requirements, across all the energy sources and sinks that are under management. The practical merit of this objective function is that it is sensitive to the match between an energy source and its use. This can be illustrated by considering the example of a home whose primary energy source for heating and appliances is grid electricity, but is also equipped with a micro wind generator, and with solar water heating. Depending on the time of day and the weather, the domestic hot water could be heated with either of the renewable energy sources or with mains electricity. The First Law energy efficiency in all cases would be close to 100%, but the exergy efficiency of using electricity from the micro wind generator would be poor, around 20%, whereas the exergy efficiency of using the solar water heating will be about 80%. So for this home, if the exergy loss inherent in grid electricity is also known, then a suitable control unit can make accurate decisions simply on the basis of minimising exergy loss, across all the energy sources at its disposal.

Since this research aims to improve the integration of domestic electricity generators and loads with the national electricity generation and distribution system, it is essential that minimisation of exergy loss is also an effective mechanism for managing this relationship. To investigate this key point modelling studies have been performed which illustrate how minimisation of exergy loss can be employed to meet the critical need for flexible demand side management identified in 2.5 and 2.6.3, and can also be used to despatch domestic micro CHP. The methods employed for these modelling studies, and the results obtained, form the main topic for this section[8].

4.6.1 The exergy loss properties of mains electricity

In order to inform a domestic control unit of the exergy loss property of mains electricity, a signal must be provided to it that indicates for each kWh of delivered electricity, the proportion that was lost of the exergy in the sources used to generate it. In response it will seek to place demand where the loss in minimised, and despatch a micro CHP when the avoided exergy loss through substitution of local generation for mains electricity is greatest. The issues arising from large scale wind generation discussed in 2.5 indicate that the desirable outcomes from demand side management should be that peak load is reduced, and demand is moved to times when there is ample wind generation, and away from times when it is at a low level. As long as the exergy loss of grid electricity increases with demand, and reduces as the proportion of wind generation in the fuel mix increases, then these outcomes should be achieved. It is also necessary that the movement of demand to a time when exergy loss is lower does not increase carbon emissions. So the exergy loss of mains electricity has been investigated to see if it has these properties.

The simplest expression for exergy E uses the Carnot coefficient:

$$E = Q(T - T_0)/T \qquad (4.1)$$

where Q is a quantity of heat at temperature T with surroundings at T_o. Thus the exergy content of the heat in the circulating hot water of a central heating system operating at 333 K, with an outside temperature at 272 K (the temperature typically used to calculate heating system capacity in the UK), is 18.3%. The overall exergy efficiency of such a central heating system with a condensing gas boiler operating with a 90% First Law efficiency is the product of First and Second Law efficiencies i.e. 16.5%. The exergy efficiencies of conventional electricity generation in the UK for different fuels have been calculated by Hammond and Stapleton (2001), and are given in Table 4-2. For

[8] Published in Applied Energy (Boait *et. al.* 2007).

comparison electricity generation by natural gas fired micro CHP is also included, as measured using the test bed instrumentation for the Whispergen unit described in Chapter 3.

Energy source	**Exergy efficiency**
Coal	33.5
Oil	33.5
Natural gas	32.1
Nuclear	37
Hydropower	78
Gas-fired micro CHP	51.9

Table 4-2 Exergy efficiencies of electricity generation (Hammond, 2001)

Using this data (and taking the figure for hydroelectric generation as applicable for wind power), the exergy loss in generating electricity over the year April 2004 to March 2005 has been calculated, starting with UK annual fuel mix data that electricity supply companies are obliged to publish (ElectricityInfo.Org 2008) under the 2005 Electricity Fuel Mix Disclosure Regulations. This was combined with the merit order in which plant is despatched (Brown 2005), which varies seasonally due to the winter increase in gas prices experienced in recent years. Table 4-3 shows the weightings in the fuel mix of different fuels in summer and winter, and also their carbon intensity as published by ElectricityInfo.Org (2008). The "other" category comprises mainly oil and inter-connector imports.

Fuel	Weight % (December 2004)	Weight % (August 2004)	Carbon intensity kg CO_2/kWh
Coal	47	4	0.91
Natural gas	30	60	0.36
Nuclear	17	27	0
Renewables	3	5	0
Other	2	4	0.5

Table 4-3 Fuel mix and carbon intensity (Brown, 2005 and ElectricityInfo.Org, 2008)

Half-hourly electricity demand data for 2004-5 are available from Elexon (2008), and was used in combination with the merit order and the fuel mix profile for the month to calculate daily exergy loss profiles and carbon intensities. As long as the variable element of electricity demand is met by generators whose exergy loss and carbon intensity is greater than the average exergy loss and carbon intensity of the baseload generation, then exergy loss and carbon intensity will rise with demand. For recent years, the price of gas and coal has been such that in summer the combination of renewables and nuclear power meets about half of the baseload, and the balance is met with gas and a small oil element. Variable demand is met with a mixture of gas and coal generation. In winter there is a substantial coal fired component in the baseload, and the mix for variable demand has more coal because of its improved position in the merit order. This seasonally varying fuel mix does deliver the desired relationships as shown in Table 4-4; similar results confirming the high marginal carbon intensity of UK electricity generation have been published by Bettle *et. al* (2006).

Season	Baseload exergy efficiency %	Baseload carbon intensity kg CO_2/kWh	Variable load exergy efficiency %	Variable load carbon intensity kg CO_2/kWh
Summer	37	0.21	33	0.6
Winter	36	0.56	33	0.7

Table 4-4 Seasonal exergy efficiency and carbon intensity for electricity generation meeting baseload and variable demand

It can be seen that if the fuel mix evolves as predicted by the DTI in Table 4-1, the expansion of renewables will more than compensate for the decline in nuclear power, so the high exergy efficiency and low carbon intensity of the baseload generation will be maintained. If nuclear power eventually expands, the position of baseload will be further improved in this respect. The higher levels of variable load (such as the early evening peak) are likely to be met using fossil fuels for the foreseeable future. As carbon capture is introduced, such plant is likely to be employed where possible for baseload because of its high capital cost. While its carbon emissions will be low, the exergy efficiency is also likely to be lower than conventional plant because of the losses in the carbon capture process. So its effect may be to slightly degrade the average exergy efficiency of the generation meeting the baseload, but it is very unlikely that the balance between baseload and variable load efficiencies will be destabilised. Another factor reinforcing the desired relationship between exergy efficiency and load is the increase in resistive (I^2R) losses as demand rises.

The resulting exergy loss profile that could be provided as a control signal to a domestic energy management system is shown in Figure 4-2, for a winter weekday. Since the exergy loss does not vary widely during the day, and the receiving control system only needs to know relative rather than absolute values, it is plotted as deviation in percentage points from the mean for the day of 64.7%. Because the amount of generating capacity from each fuel type in the merit order is unchanging during the day, it tracks demand exactly.

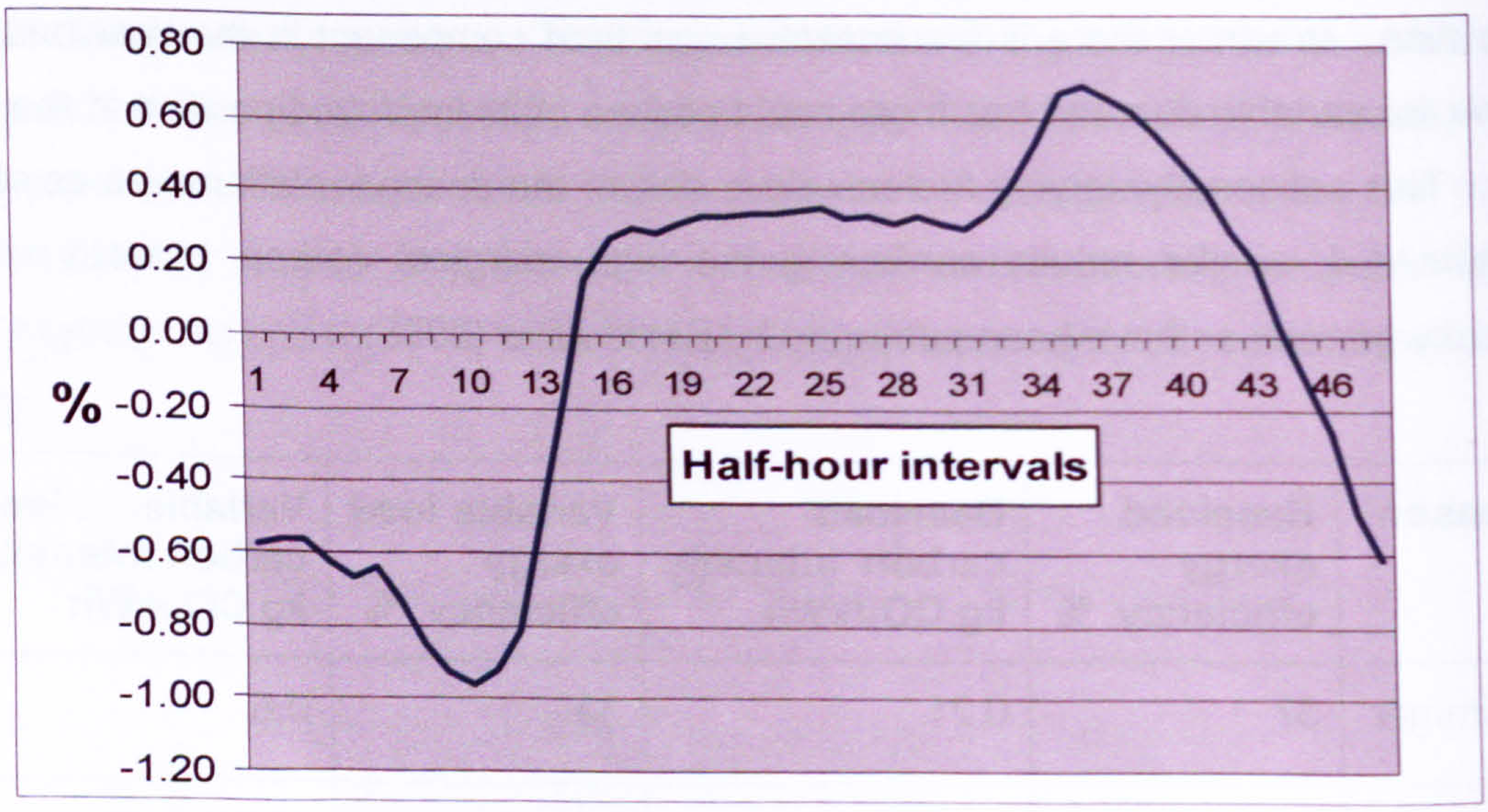

Figure 4-2 Exergy loss of UK grid electricity generation on 1 February 2005 expressed as deviation from mean of 64.7%

This exact tracking of demand will change as the proportion of renewables in the fuel mix increases. Figure 4-3 shows a modelled profile resulting from a scenario in which wind generators represent about 30% of plant capacity (corresponding to a typical contribution to the fuel mix of 9%). At the start of the day shown a winter anticyclone has caused the actual wind output to average about 6% of the fuel mix during the first 6 hours. During the day a fall in atmospheric pressure drives wind output to 14% of the fuel mix in the last 6 hours, resulting in a progressive improvement in the exergy loss profile. This is a realistic and potentially common scenario, as the analysis of UK wind generator performance by Sinden (2007) demonstrates.

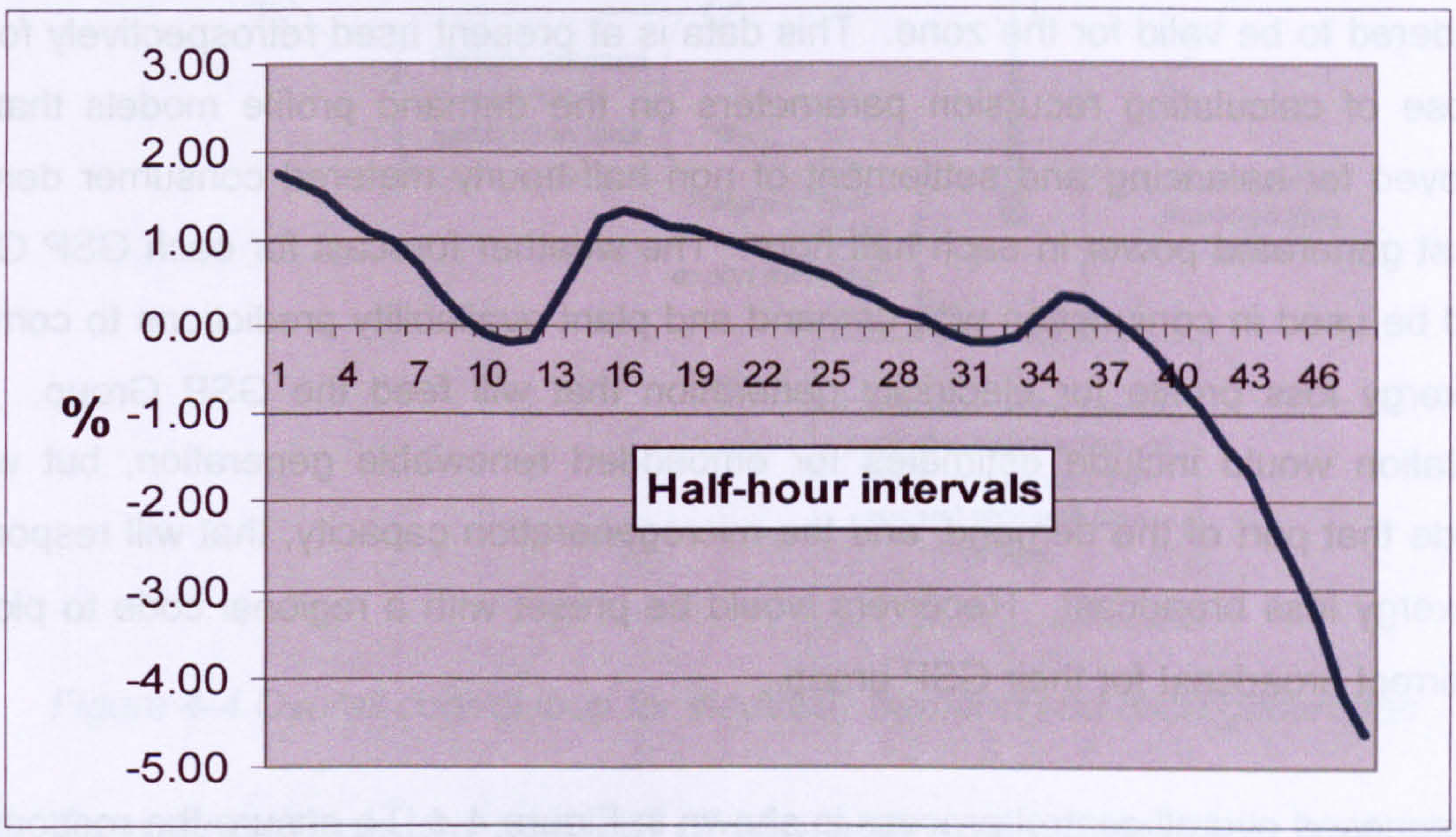

Figure 4-3 Modelled exergy loss of UK grid electricity generation with wind intensity variation, expressed as deviation from mean of 60.8%

It can be seen that a domestic control unit responding to these exergy loss profiles will behave quite differently in each case. Given the profile in Figure 4-2, it will seek to move demand away from, or micro CHP generation towards, the early evening peak. In the scenario of Figure 4-3, demand will be pushed later in the day and micro CHP drawn into the morning peaks. These responses will of course be limited by the need to meet the energy needs of the occupants as a first priority as recognised in 4.1.

4.6.2 Use of an exergy loss profile for demand side management

Having demonstrated that an exergy loss profile for mains electricity provides the right incentives to an exergy-optimising control unit, the next step was to investigate what might happen if this were to be implemented on a large scale, bearing in mind the concerns of this study that aggregate behaviour should be benign. To provide a practical concept by which this might be achieved, it is proposed that the exergy loss profile should be broadcast using the Radio Teleswitch system described in 2.6.3. This is a proven technology with spare capacity that could be used for the 48 values of exergy loss in a daily profile. It would be a simple and relatively low cost engineering task to integrate a Teleswitch receiver into the control unit.

Because of the weather dependency of exergy loss, it is proposed that the profile to be broadcast daily would be calculated for each of the existing Grid Supply Point Groups (GSP Groups). These are defined regional zones within the UK electricity distribution system; each has an identified location at which meteorological data is collected and considered to be valid for the zone. This data is at present used retrospectively for the purpose of calculating recursion parameters on the demand profile models that are employed for balancing and settlement of non half-hourly metered consumer demand against generated power in each half hour. The weather forecast for each GSP Group would be used in conjunction with demand and plant availability predictions to compute an exergy loss profile for electricity generation that will feed the GSP Group. This calculation would include estimates for embedded renewable generation, but would exclude that part of the demand, and the microgeneration capacity, that will respond to the exergy loss broadcast. Receivers would be preset with a regional code to pick up the correct broadcast for their GSP group.

The proposed overall control process is shown in Figure 4-4. To ensure the response to the broadcast is near optimal, the initial calculation of an exergy loss profile for the day is tested by modelling the response using historic metering data. Ideally the responding demand should fill troughs in the profile level, like water poured into a depression, while controlled microgeneration should reduce peaks evenly to a lower level. If prediction of the response shows this will not happen, perhaps because a particularly high or low value for exergy loss in a half-hour interval is excessively attractive in the optimisation calculation performed by individual domestic controllers, then a small adjustment can be made to that half-hour interval and/or the adjacent slots to level the response. National Grid may also wish to make adjustments to the profile to deal with exceptional plant availability problems, or "TV pickup". In this way the exergy loss broadcast can be used as a balancing tool. This adjusted profile is then broadcast over Radio 4 using the existing Radio Teleswitch facility, and the actual response in individual households is measured using half hour metering.

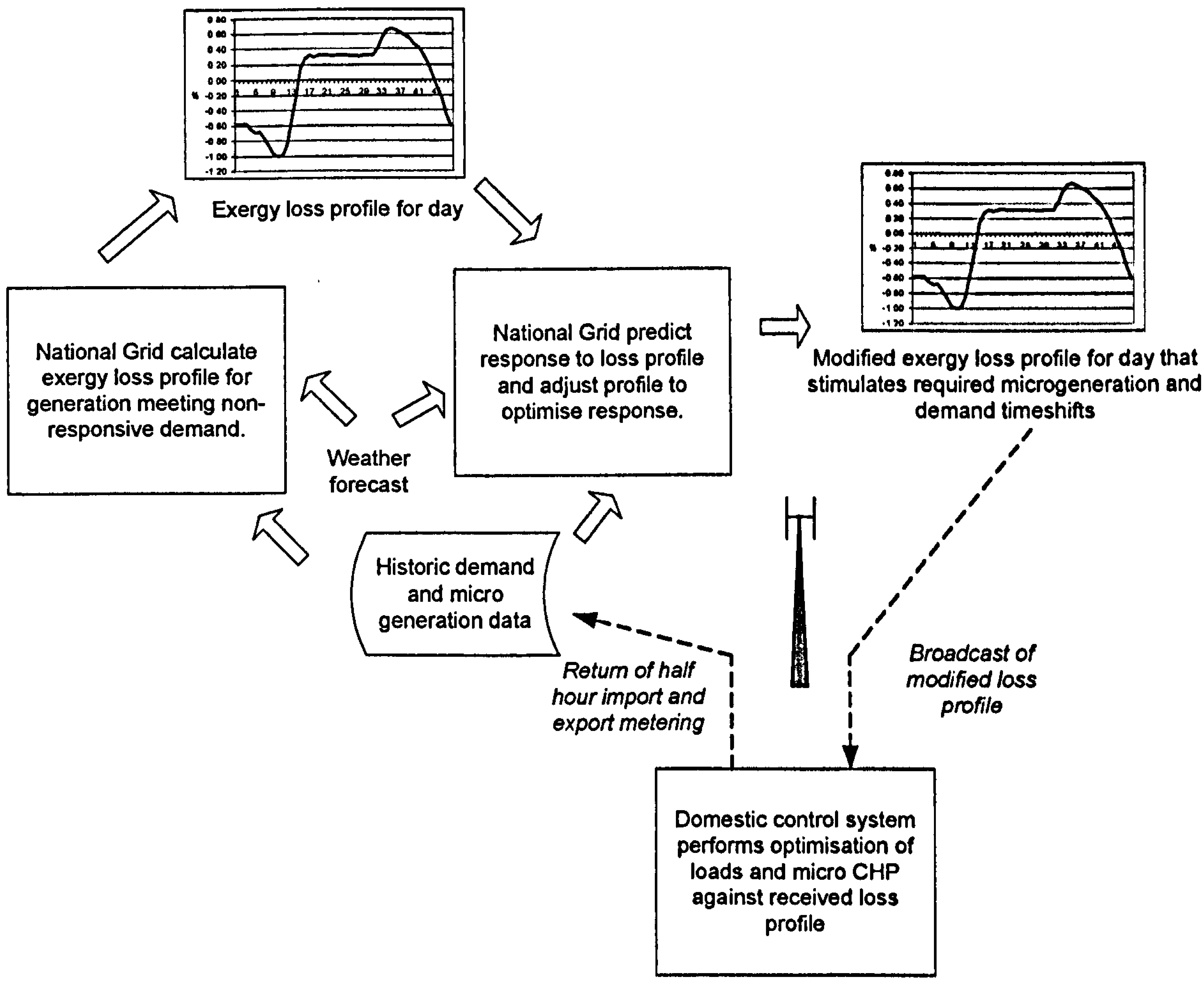

Figure 4-4 Overall control loop for electricity demand and microgeneration

4.6.3 Exergy optimising control of storage and immersion heaters

Electric heating using convector units with thermal storage (storage heaters) is an established method of heating in the UK currently employed in about 1,500,000 homes. As discussed in 2.6.3, they are currently operated under the limited form of demand management provided by the Economy 7 scheme. These homes have their domestic hot water supplied by an electrical immersion heater that is usually also supplied from the Economy 7 controlled wiring circuit within the home. So modelling a controller for storage and immersion heaters that can respond to the exergy loss broadcast provides a suitable example of the functions that have to be performed, and the effect on a large scale. This section describes the optimising algorithm modelled as operating within the controller, and the results from a national scale model. For convenience a list of symbols used in this and subsequent optimising algorithms is given in Table 4-5.

a,b,c,d	Half-hour intervals from the diurnal cycle in which heating start (*a,c*) and stop (*b,d*) events occur
C_h	Thermal capacity of house (kWh/°C)
E, E_L	Exergy, exergy loss (kWh)
H_i	Heat output of microCHP (kW) in *i*th half-hour interval
L_i	Proportion of exergy lost in *i*th half-hour interval
P_i	Electrical power consumed or generated in *i*th half-hour interval (kW)
Q	Thermal energy (kWh)
T, T_s, T_e, T_r	Temperature, (setpoint, external, room)
T_{rm}, T_{re}, T_{ri}	Predicted room temperature (morning, evening, *i*th half-hour interval)
T_{em}, T_{ee}, T_{ei}	Predicted external temperature (morning, evening, *i*th half-hour interval)
t_i, t_m, t_e	Duration of energy input during *i*th half-hour interval, duration of morning and evening heating sessions
W_h	Heat loss rate of house W/°C of temperature difference between interior and exterior
η_e, η_h	Electrical efficiency and thermal efficiency (of CHP unit)

Table 4-5 Symbols used for optimisation models

A storage heater has to capture sufficient energy to meet the heat load of the house over 24 hours, with the least possible exergy loss. It is assumed that the occupants can set morning and evening time intervals t_m and t_e during which sufficient heat must be supplied to achieve a room temperature set point T_s. When the morning heating session starts at half-hour interval a there must have been sufficient heat provided to recover the setpoint T_s. Then by the time tm is over at half-hour interval b sufficient heat must have been provided to sustain T_s during that period. Equivalent heat budgets exist for the start of the evening heating session at half-hour interval c, and the session finish at d. These four heat budget reference points expressed as cumulative energy inputs provide four constraint inequalities giving an objective function:

Minimise $E_L = \sum_{i=1}^{48} P_i L_i t_i$ with the constraints:

$$\sum_{i=1}^{a} P_i t_i \geq C_h (T_s - T_{rm}) \tag{4.2}$$

$$\sum_{i=1}^{b} P_i t_i \geq C_h (T_s - T_{rm}) + (T_s - T_{em}) W_h t_m \tag{4.3}$$

$$\sum_{i=1}^{c} P_i t_i \geq C_h(T_s - T_{rm}) + (T_s - T_{em})W_h t_m + C_h(T_s - T_{re}) \tag{4.4}$$

$$\sum_{i=1}^{d} P_i t_i \geq C_h(T_s - T_{rm}) + (T_s - T_{em})W_h t_m + C_h(T_s - T_{re}) + (T_s - T_{ee})W_h t_e \tag{4.5}$$

The predicted morning and evening external temperatures T_{em} and T_{ee} are broadcast with the exergy loss data. Over time the controller can calculate the house thermal capacity C_h and specific heat loss L_h from its own records of the room temperature T_r making use of the supplied external temperature T_e. It can also predict the room temperatures at the start of each morning and evening heating interval (T_{rm} and T_{re}) from T_e. The controller solves the problem formulation using a conventional linear programming technique (the model uses the Simplex method), and draws electrical power P_i over time interval t_i during the ith half-hour interval to charge the storage heater.

A similar problem formulation can be employed for control of the immersion heater. The occupants set time intervals when hot water is required, and the controller brings the water up to temperature prior to the start of each time interval while minimising exergy loss. In the model it is assumed that the water cylinder is well insulated so that, for example, it can be heated during the overnight demand trough for use the next morning.

This optimisation algorithm was modelled for storage heaters in 200,000 homes, and 1,000,000 domestic immersion heaters distributed nationwide. Figure 4-5 shows the total national electricity demand in each half-hour interval for 1 Feb 2005, with the response of the controlled appliances to the exergy loss profile (Figure 4-2) that would have been broadcast, under a control regime as described in 4.6.2. Where the demand from these appliances under control differs from that actually likely to have taken place on that date, the reduction in demand is shown. It can be seen that storage heater demand is delayed from its conventional Economy 7 timing to the early morning demand trough, which is also filled by water heating. Some water heating is also delayed from the early evening peak providing a useful reduction in demand.

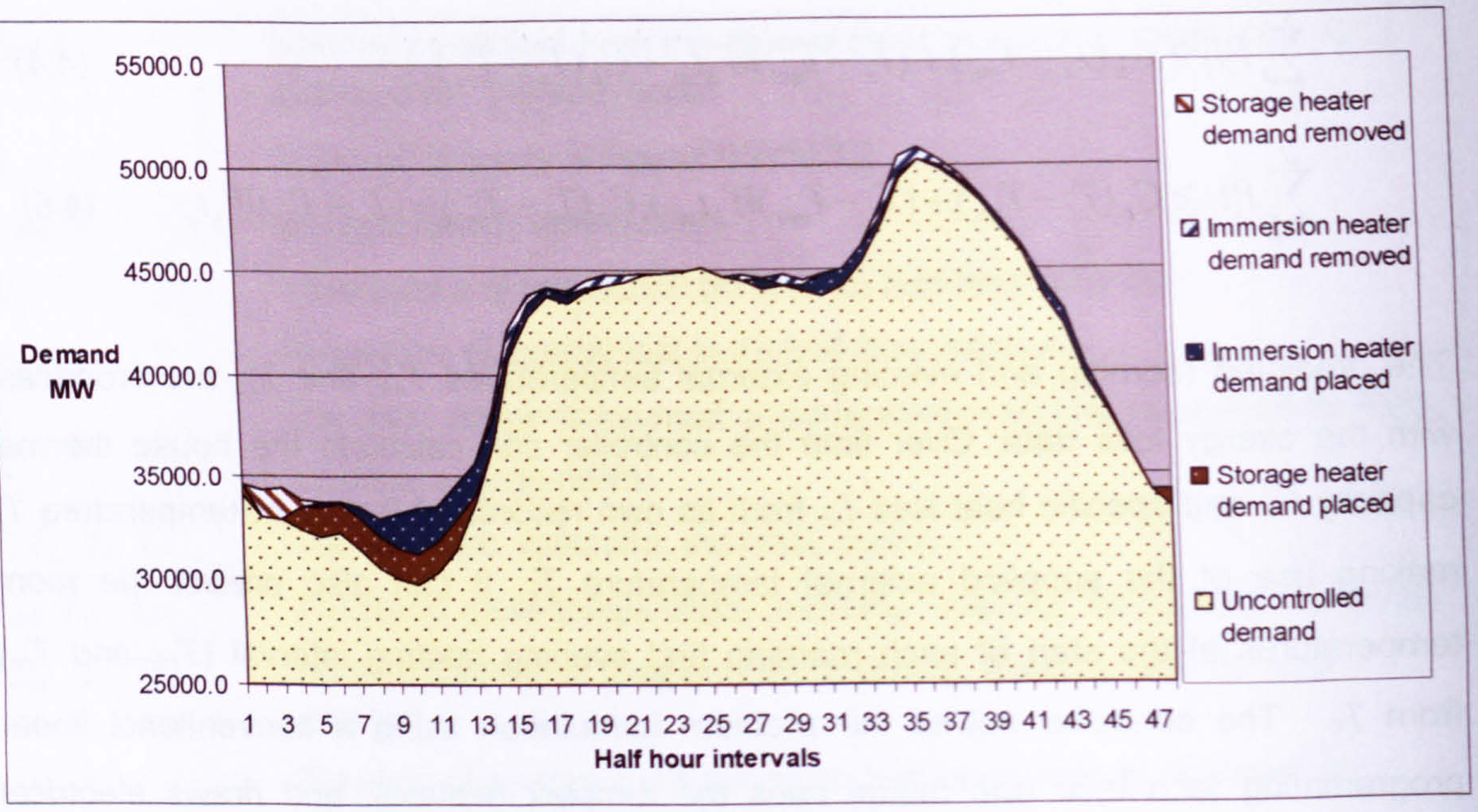

Figure 4-5 Modelled response of storage and immersion heaters to exergy loss profile of Figure 4-2 (constant renewables element in fuel mix)

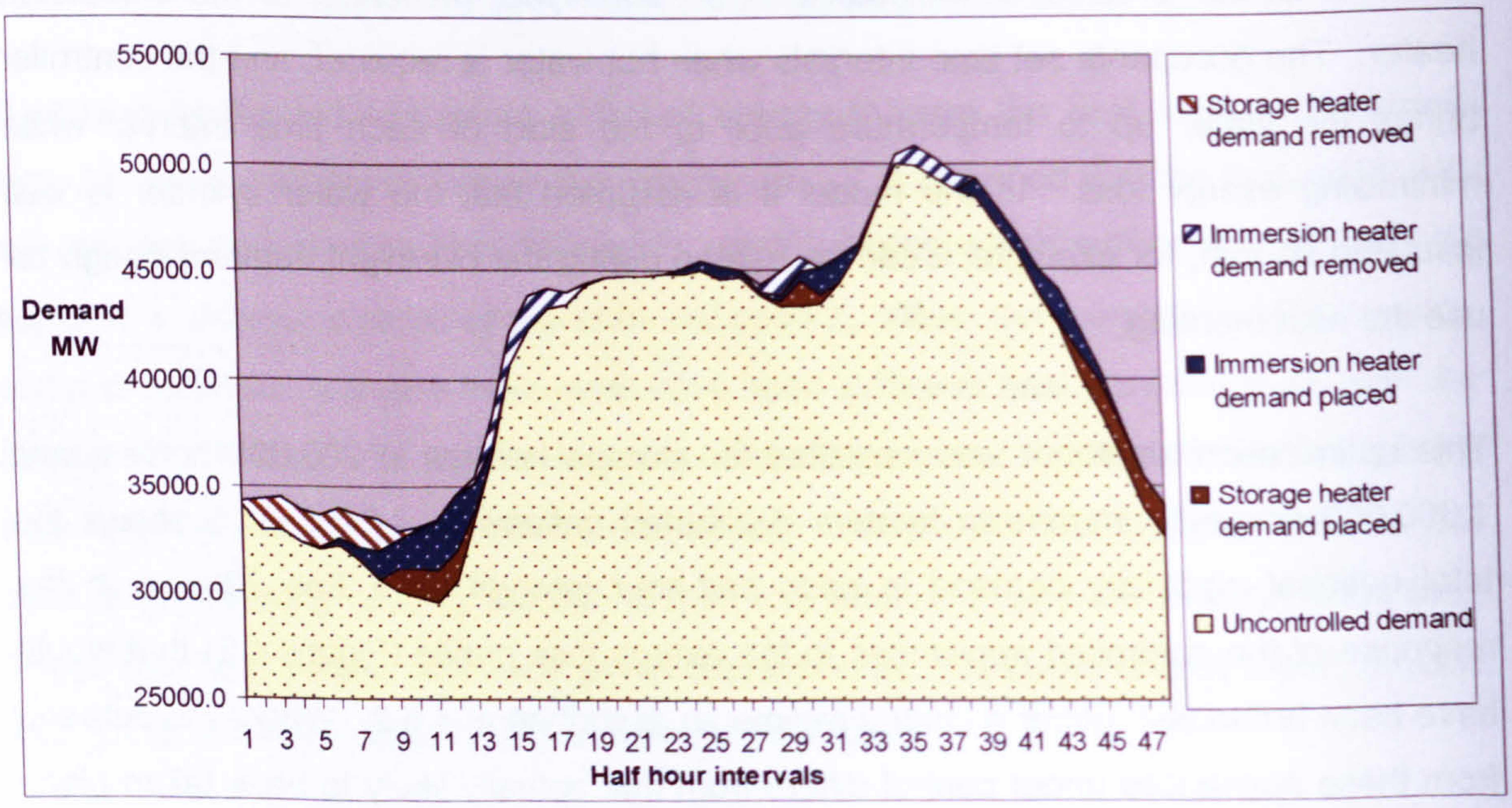

Figure 4-6 Modelled response of storage and immersion heaters to exergy loss profile of Figure 4-3 (variable wind component in fuel mix)

The benefits of this proposal when generation from renewable sources is fluctuating can be seen in Figure 4-6. This scenario employs the same population of appliances under control as Figure 4-5, but with the exergy profile resulting from a rise in wind generation as shown in Figure 4-3. Now storage heater demand is placed throughout the day, taking advantage of local exergy loss minima to meet the conditions given in inequalities (1)-(4). The filling of the early morning demand dip is at a slope parallel to the falling trend of exergy loss, and water heating demand is moved from the morning and evening peaks.

The exergy loss profiles used to generate these responses are as dictated by the fuel mix; they do not have any of the optimising adjustments mentioned in 4.6.2 as desirable for a practical system. The need for such small adjustments can be seen in the way the filling of the morning trough in Figure 4.5 is not quite flat.

4.6.4 Exergy optimising despatch of micro CHP

In Chapter 3 it was noted from test bed experiments and modelling that a small variation in room temperature setpoint could be used to alter the time of day at which heat demand, and consequent electricity generation, occurs. Figure 3-6 illustrates how a 2°C rise in setpoint during the day can transfer the bulk of the generator output from the morning to the afternoon, including the late afternoon demand peak. So as long as the occupants are comfortable with a small rise in temperature during the day then production of electricity generated with high exergy efficiency can be stimulated at a time when it offsets grid electricity produced with poor exergy efficiency. The validity of the assumption that this rise is acceptable to occupants is considered later in this chapter.

Thus to model the despatch of micro CHP an initial assumption has to be made of the maximum amount that the room temperature set point can be raised to stimulate output (δT_{max}); in the modelling described below this was limited to 1°C. The set point can only be usefully raised when the heat output of the CHP unit is not fully loaded at the default set point, so the controller has to use the external temperatures provided in the broadcast, combined with the user's heating time settings, to determine half-hour intervals when there will be spare capacity that could be used. The controller can also calculate what fraction δT_i of δT_{max} could actually be used in a given half-hour interval with spare capacity. Having identified half-hour intervals where despatch can occur, the controller as modelled then executes a linear programming calculation to decide which will avoid the most exergy loss by substituting for large scale generation. The setpoint is then raised incrementally in the most attractive half-hour intervals whose total available capacity is equivalent to a setpoint uplift not exceeding δT_{max}. Treating CHP generator output P_i as negative demand gives the optimisation problem formulation with inequalities (4.6)-(4.8):

Minimise $E_L = \sum_{i=1}^{48} -P_i L_i t_i$

With the constraints:

$$H_i t_i = \delta T_i C_h \leq \frac{1}{2}(H_i - (T_s - T_{ei})W_h) - (T_s - T_{ri})C_h \qquad (4.6)$$

for all timeslots $i = 1 \rightarrow 48$,

$$P_i = \frac{\eta_e}{\eta_h} H_i \qquad (4.7)$$

$$\sum_{i=1}^{48} \delta T_i \leq \delta T_{\max} \qquad (4.8)$$

The factor of ½ in the first inequality is simply the half hour duration of the half-hour interval, on the assumption that the energy units used are kWh. The CHP efficiency ratio η_e/η_h provides the electrical power output of the CHP unit for a given heat output.

The modelled behaviour of micro CHP units subject to this control method is shown in Figure 4-7, in comparison with the operation of uncontrolled micro CHP responding only to heat demand with a constant setpoint. The demand and exergy loss profiles used are same as Figure 4-5; the effect of the control is to move some generator output from the early morning (the diagonal shaded area) to the early evening peak (dark shading). A population of 5,000,000 units with a 1kW peak electrical output was modelled; this is consistent with the microgeneration scenarios for 2050 described in DEFRA (2004). In practice this level of capacity is more likely to be reached with a smaller number of units and a spread of output levels to 5kWe and above as micro CHP is employed in business premises as well as homes. It is evident that if both immersion heaters and micro CHP were under control as shown in these models the early evening peak would be reduced by about 2.5 GW. Demand variability is also reduced; for the day shown the standard deviation of net demand is 6.0 GW, this would reduce to 5.4GW with control exercised as shown in Figures 4-5 and 4-7.

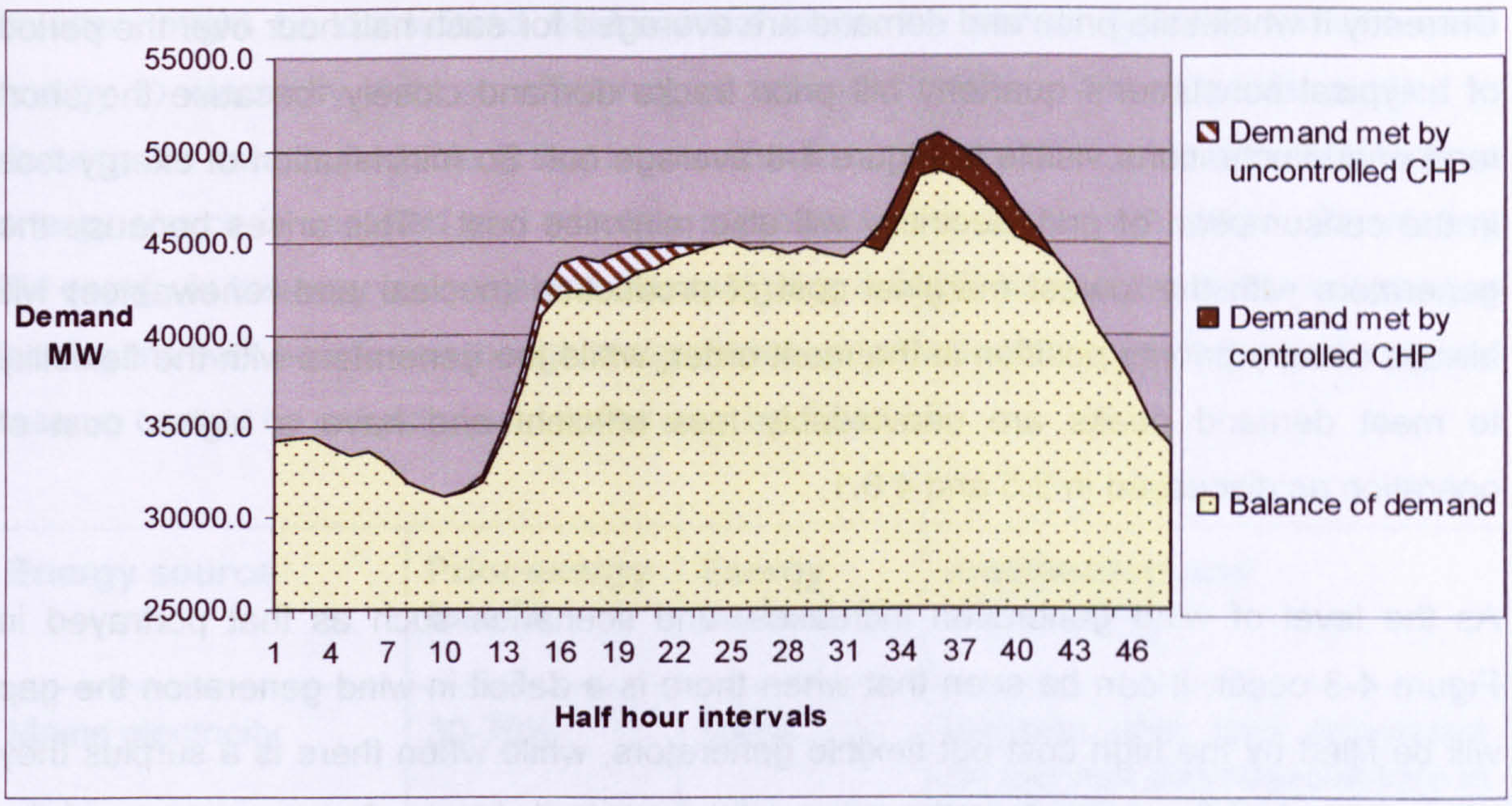

Figure 4-7 Modelled response of micro CHP to exergy loss profile of Figure 4.2 (constant renewables element in fuel mix)

4.6.5 Effect of exergy loss minimisation on cost

These investigations into the exergy loss properties of mains electricity and the operation of an exergy-optimising control unit have confirmed that minimising exergy loss will also minimise the carbon emissions arising from electricity generation. Similar arguments also apply to the cost of electricity generation – Figure 4-8 below illustrates how the wholesale price of electricity tracks demand. The system buy price is the rate that an electricity supplier who is under supplied by their generation contracts must pay to clear the deficiency, so it is quite volatile.

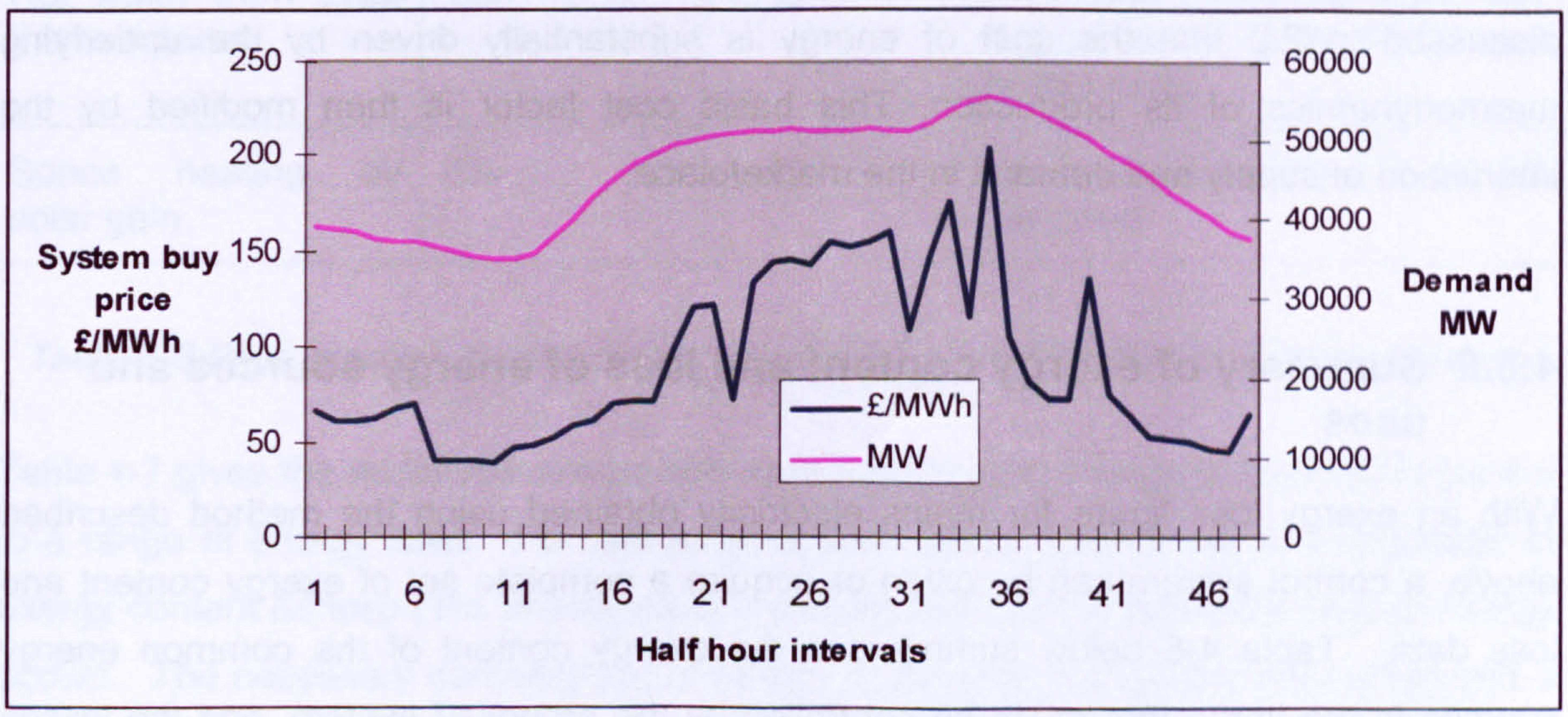

Figure 4-8 Electricity demand and system buy price for 4 January 2008 (Elexon 2008)

Currently if wholesale price and demand are averaged for each half hour over the period of a typical consumer's quarterly bill price tracks demand closely, because the short term price fluctuations visible in Figure 4-8 average out. So minimisation of exergy loss in the consumption of grid electricity will also minimise cost. This arises because the generators with the lowest marginal cost of production (nuclear and renewables) will always occupy priority position in the merit order, while the generators with the flexibility to meet demand peaks are unavoidably less efficient and have a higher cost of operation as discussed in 2.5 and 4.6.1.

As the level of wind generation increases, and scenarios such as that portrayed in Figure 4-3 occur, it can be seen that when there is a deficit in wind generation the gap will be filled by the high cost but flexible generators, while when there is a surplus they will keep out of the market as the price will be pushed down. A consequence of the Government's policy of awarding ROCs (worth currently about £45 per MWh) to renewable generators is that even if the market price falls to zero it will be economically advantageous to operators of wind generators to keep supplying the grid. The shape of the wholesale price profile will therefore continue to be similar to that of exergy loss, hence cost minimisation should also be sustained.

While the shape of the wholesale electricity cost profile is similar to exergy loss, its absolute values will vary considerably from season to season and year to year. Conversely, exergy loss while weather dependent will be highly predictable in absolute terms since long term changes will only arise from introduction of new electricity generating plant such as carbon capture. These observations support the hypothesis discussed in 2.2 that the cost of energy is substantially driven by the underlying thermodynamics of its production. This basic cost factor is then modified by the interaction of supply and demand in the marketplace.

4.6.6 Summary of exergy content and loss of energy sources and uses

With an exergy loss figure for mains electricity obtained using the method described above, a control system can be given or acquire a complete set of exergy content and loss data. Table 4-6 below summarises the exergy content of the common energy sources in the home that might be controlled by the proposed system, and the losses that have been incurred in delivering them to the point of use. The use of a figure of 6% for the prior exergy losses of PV electricity, reflecting only the losses in the DC/AC inverter, might be considered controversial since the panels typically convert solar energy to electricity with an efficiency of around 12-15%. The rationale applied in deriving the data in the table is that losses should only accrue from the point at which an energy source is captured and enters a processing and distribution chain. So treating PV energy in this way is consistent with assigning a 100% exergy content to natural gas leaving the well head even though a significant proportion of the gas in the underground reserve cannot be extracted and some may be flared off.

Energy source	Prior exergy loss %	Exergy content %	Justification and assumptions
Mains electricity	30-70%	100%	Variable prior loss dependent on fuel mix and resistive loss in distribution.
Mains gas	10%	100%	Prior loss from distribution pumps and leakage in SW England (Wales and West Utilities 2007).
Electricity from PV panel	6%	100%	Inverter losses (SMA 2002).
Electricity from micro wind generator	6%	100%	Inverter losses (SMA 2002).
Electricity from micro CHP	53%	100%	As measured for test bed CHP unit (heat led), including gas distribution losses.
Hot water from solar thermal panel	4%	17%	Prior loss measured from test bed pipework, with 45 °C exit temperature.
Space heating by solar gain	0%	8.5%	Internal temperature of 22 °C assumed.

Table 4-6 Prior exergy loss and exergy content for common domestic energy sources

Table 4-7 gives the additional exergy loss from applying the energy sources in Table 4-5 to a range of energy uses. For this purpose loss arises when there is a mismatch in exergy content between the energy source and the use, hence avoidable loss of exergy occurs. The necessary consumption of exergy in the end use itself is not considered a loss. Note the solar thermal sources are not included because it is assumed that the hot water and warm air they produce are desired end use outputs, so there is no additional loss.

Energy source	Energy use	Exergy loss %	Justification and assumptions
Electricity (however generated)	Entertainment appliances and lighting	0%	Ignores inefficiency with which information or light is delivered.
	"Wet" appliances with cold fill	89%	Water mains feed assumed to be at 10 °C with heating to 40 °C.
	Immersion heating of hot water	82%	Water heating to 60 °C, room temperature of 22°C, 4:1 coefficient of performance assumed for heat pump.
	Space heating by thermal storage radiators	91.5%	
	Space heating by heat pump	69%	
Gas	Hot water heating (condensing boiler)	84%	92% First Law boiler efficiency assumed, otherwise as for electrical heating.
	Space heating (condensing boiler)	91%	
Hot water from solar panel	Hot water heating	0%	For test bed solar hot water panel there are no heat exchanger losses.

Table 4-7 Exergy loss arising when applying energy sources to domestic uses

With the data shown in Tables 4-6 and 4-7 a control unit can employ the linear optimisation techniques illustrated in 4.6.2 and 4.6.3 to resolve complex optimisations, such as the best time to run a wet appliance drawing a hot fill where the household is equipped with solar hot water heating and a micro CHP unit.

4.7 Other Requirements

So far this chapter has focussed on the justification and practical application of conservation of exergy as an objective function. The other implications of the hypothesis for a domestic control system (as deduced in 2.2) also need to be investigated. These are that it should:

- exploit energy storage opportunities;
- overcome constraints on the information available to control processes that arise from the user's limited attention span and comprehension;

- facilitate complexity and diversity in energy capture and conversion.

This section addresses these points, and also considers any remaining topics relevant to realisation of the aims.

4.7.1 Exploitation of storage

The energy stores that are readily available in most dwellings are those comprising an insulated thermal mass, in particular the fabric of the building, hot water storage tanks, and of course storage heaters. The traditional construction methods for UK homes, comprising a cavity wall of brick and/or cement block construction with a plastered internal finish tends to give a high thermal capacity because of the high specific heat of these materials relative to their volume. Cavity wall insulation is also helpful in creating an energy store because it allows most of the inner leaf of the wall to reach room temperature. Few homes in the existing building stock will not have at least one of these three stores.

While only low exergy thermal energy can be stored in this way, exergy loss can often be reduced by time-shifting the unavoidable consumption of a high-exergy source to meet a low exergy use. The despatch of micro CHP by manipulation of the room temperature set point as described in 4.6.4 is an example of this technique – heat is stored in the building fabric when electricity is desired, and drawn out later when the CHP is not operating. To allow an energy management system to exploit these storage resources effectively it needs three data items:

- the thermal capacity of the store;
- the heat loss rate;
- the temperature range through which the store can be charged and then be allowed to fall.

The first two of these parameters are readily obtained by measuring the energy input to the store, and the resulting rise and fall of temperature over a charge and discharge cycle. Practical methods for performing these measurements are discussed in the next chapter. The last item is more difficult because it depends on the temperature preferences and needs of the occupants. Table 4-8 summarises the upper and lower temperature bounds for the three commonly available thermal stores.

Thermal energy store	Upper temperature limit	Lower temperature limit
Hot water cylinder	60°C required to kill bacteria	In range 40 °C to 50 °C as required by occupants
Storage radiator	Determined by manufacturer – around 250 °C	In range 15 – 22 °C dependent on occupant tolerance and lifestyle
Building fabric	In range 18 – 24 °C dependent on occupant requirements	In range 15 – 22 °C dependent on occupant tolerance and lifestyle

Table 4-8 Temperature bounds for common domestic thermal energy stores

The lifestyle of occupants is a factor in the lower temperature limits for stores contributing to space heating, because in a home which is unoccupied for some part of the day room temperature can be allowed to fall below the normal comfort range. In 2.6.4 it was shown that occupants are often unable to inform current control systems of their occupancy patterns and temperature preferences because of the over-complex human interface these systems present. So to make best use of these thermal stores it is essential that a method is developed to determine occupancy patterns and temperature settings accurately, either automatically or through an improved human interface, or both. A weather forecast is also desirable so that heat loads and hence discharge rates can be predicted, ideally taking into account external temperature, wind speed, and solar gain – methods for providing this forecast are considered in Chapter 5.

An alternative form of energy storage has already been considered in 3.4, where the concept of a microgrid with electrical storage of 2.7kWh per household was tested, and found to be feasible given sufficient PV generator capacity (about 3kWp per household). This suggests that the energy management system should be capable of making use of electrical storage. The advent of the "plug-in hybrid" car makes this a practical possibility - many authors such as Romm (2006) believe this is the most promising technology for mitigating carbon emissions from vehicles. Plug-in cars obtain most of the energy for short journeys up to about 100km from a rechargeable battery pack, and use the internal combustion engine for greater distances. For example, conversions of the Toyota Prius to plug-in operation are now being performed (Battery Vehicle Society 2008) which replace the standard 1.3kWh nickel-cadmium battery pack with a 7kWh lithium iron phosphate unit. Higher capacities can be expected as the technology matures.

Since the average car only spends 1-2 hours a day travelling, and recharge time for this size of battery is also about 1-2 hours, it is clear that there is plenty of time when the car could be connected to the electricity supply at home or at work and contribute its storage capacity to local energy management. The additional charge-discharge cycles performed by the battery would have some effect on its life, and would involve exergy loss, but this could be readily taken into account by the proposed energy management system in deciding when to draw on the battery. This concept also requires the system to obtain an understanding of the car user's lifestyle and behaviour patterns, so that it can ensure their car is charged to a suitable level when they need it.

4.7.2 The human interface and temperature requirements for comfort

The simplest form of human interface for a domestic energy management system would be to have none at all – the system should automatically acquire all the information it needs to provide comfort and efficiency. Given the research background discussed in Chapter 2 at first sight this seems a desirable goal that should be approached as closely as possible. However some form of human interface is unavoidable, for two purposes. Firstly, to provide useful information to the occupants in accordance with the third aim of this project cited in Chapter 1. This information should encourage the occupants to perform those control actions which the system is unable to execute itself, such as turning off unwanted entertainment appliances. Secondly, to allow occupants to intervene when an exceptional circumstance arises, such as a sick person needing more warmth.

To allow the human interface to be limited to these essential purposes, the data items normally provided manually that the system should acquire itself wherever possible are:

- the timing of routine occupant behaviours that are associated with a change in energy requirements, such as leaving the house to go to work;
- the room temperature settings that the occupants prefer;
- variations in desired room temperature settings that arise due to weather changes such as exceptionally cold conditions;
- times when domestic hot water is required.

The requirement to recognise behaviour patterns is addressed in Chapter 5 and a solution developed. Automatic decisions concerning internal air temperature are already commonplace – offices and shops do not normally allow occupants to change the temperature, but seem to provide adequate comfort, so it should be possible for the proposed system to set internal air temperature in the home. The established guidance for indoor temperatures is ISO 7730 (ISO, 2005) which provides an equation relating occupant comfort as expressed by Predicted Mean Vote (PMV) to air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing insulation. It would be a simple matter to take a single operating temperature from ISO 7730, based on assumed values for these parameters, which should give a reasonable PMV in many circumstances, as is frequently done for commercial buildings.

However, comfort and efficiency will be improved if the system adapts the temperature automatically where there is information relating to one of the PMV input variables. This can be derived if there is some knowledge concerning the occupant's lifestyle. For example, if the occupants are out at work during the day it is reasonable assumption that they will have a metabolic rate in the morning when getting up and dressing that is between 20% and 50% greater than that when resting late in the evening (Sherwood, 1995). So if this behaviour pattern can be recognised by the system the temperature setting can be profiled to rise during the afternoon and early evening.

There is also research evidence that PMV is dependent on outdoor temperature (T_{out}.) Humphreys and Nicol (2002a) have shown that ISO 7730 overestimates the perception of warmth at higher and lower outdoor temperatures, and derive a correction proportional to T_{out}^2. Their finding is that a monthly mean temperature is a preferred metric for T_{out}. rather than a value which reflects short term variations. They have also investigated the perception of comfort in buildings which are "free running" i.e. have no systematic heating or cooling (Humphreys and Nicol 2002b), and derived an equation for comfort temperature T_{cm}:

$$T_{cm} = 13.5 + 0.54T_{out} \quad \text{for } T_{out} > 10\,^{\circ}\mathrm{C} \tag{4.9}$$

The homes that are expected to use this control system are likely to be capable of "free running" for T_{out} > 12-15 °C because they are naturally ventilated, and solar gain and heat from electrical appliances will provide an acceptable internal temperature. Temperature tolerance is also increased by the "adaptive opportunity" (Baker and

Standeven 1995) normally available in the home i.e. the ability to change clothing, open windows, and adjust the heating if necessary.

So the proposed room temperature setting algorithm for this control system is to increase the temperature set point for T_{out} below 0°C using a linear approximation to the findings by Humphreys and Nicol, and reduce it above 10 °C to promote transition to the "free running" regime and improve efficiency. Figure 4-9 shows the resulting dependency of baseline room temperature set point on external temperature. This baseline is subject to the metabolic rate adjustment which is applied symmetrically where it is justified by the lifestyle, so that a reduction in temperature in the morning is balanced by an increase in the evening.

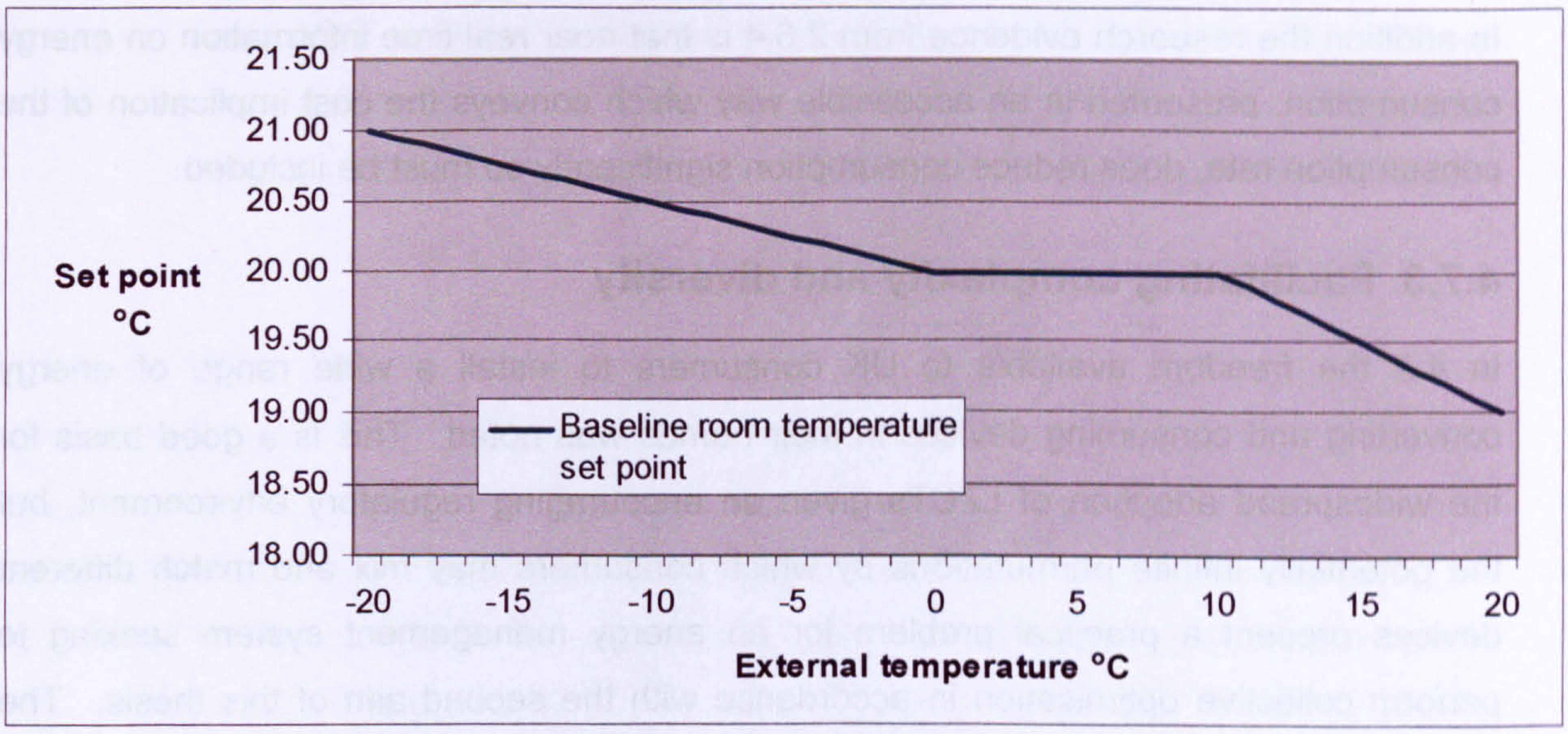

Figure 4-9 Adjustment of room temperature set point in response to outside temperature

These methods should allow automatic setting of room temperature on a routine basis, but it will important to provide a manual override so that the user's perception of having adaptive opportunity is maintained. Their practical implementation is considered in Chapter 5.

Automatic timing of domestic hot water is only an issue where a storage tank is used – where it is delivered on demand by a "combi" gas boiler or instant electrical water heater the control mechanisms are inherently quite user friendly[9] and are not amenable to supervision by an energy management system. The storage tank must hold sufficient water at temperatures between 45°C and 60°C to meet demand when it occurs. The

[9] Water temperature stability is often a problem with on demand systems but can only be addressed at the point of delivery with thermostatic mixing valves or flow rate control.

insulation on typical domestic tanks in the UK is such that cooling occurs at a rate of about 1-2°C per hour, so if usage patterns can be predicted then heat can be injected at the appropriate time, taking account of any exploitation of the thermal storage capacity as discussed above. Methods for quantifying and predicting hot water usage are discussed in Chapter 5. As for room temperature, some form of simple manual control must be maintained.

Once the system has acquired as much information automatically as possible, the question remains as to what information the system should present. Clearly there must be enough information on thermal status to allow the manual controls provided for adaptive opportunity to be used – current room temperature and some indication of the volume of usable hot water available are proposed as the essential minimum data items. In addition the research evidence from 2.6.4 is that near real time information on energy consumption, presented in an accessible way which conveys the cost implication of the consumption rate, does reduce consumption significantly so must be included.

4.7.3 Facilitating complexity and diversity

In 4.2 the freedom available to UK consumers to install a wide range of energy converting and consuming devices in their homes was noted. This is a good basis for the widespread adoption of LZCTs given an encouraging regulatory environment, but the potentially infinite permutations by which consumers may mix and match different devices present a practical problem for an energy management system seeking to perform collective optimisation in accordance with the second aim of this thesis. The system needs to know just what devices it has under management and what mechanisms for control are available. Commercial building energy management systems typically obtain this information through conventional human-computer interactions such as mouse operations on icons representing different appliances, and selection of options from drop-down lists. This approach is completely inconsistent with the simplified human interface discussed in the previous section.

What is needed is a system that allows consumers to go to their local builder's merchant or do-it-yourself store, buy a PV panel or a wind generator, and "plug & play". If they buy a solar hot water system, they will have to do some plumbing, but the system should recognise the presence of the panel, measure its key properties such as its energy output, and optimise accordingly. Ideally all likely energy capture and conversion devices should be recognised automatically by the system, and have their key performance parameters and control modes quantified. If this can be achieved, it would be a major step forward in de-skilling the installation both of LZCTs and of the energy management system itself. Simplified installation will reduce costs and also avoid the take-up of LZCTs being constrained by a lack of specialised training and experience in the plumbing and building trades. So Chapter 5 takes up the challenge of providing this "plug and play" capability in a domestic energy management system.

5 REALISATION OF AN EXERGY-CONSERVING SYSTEM

5.1 Concept

The ideal functions of a domestic energy management system carried forward from Chapter 4 may be summarised as:

- automatic acquisition of the behaviour patterns of the occupants, so that heating or cooling is only provided when it is needed;
- automatic acquisition of the temperature preferences and tolerances of the occupants, again so that heating or cooling is provided only to the extent that it is needed, and the thermal stores within the building fabric or water storage can be exploited as far as possible;
- automatic characterisation of the thermal properties of the building;
- automatic characterisation of the energy conversion devices under control or supervision within the household;
- reception of broadcasts that signal the exergy loss in mains electricity;
- prediction of external ambient temperatures and wind conditions, either generated internally from historic data captured by the system or by reception of an actual weather forecast;
- use of all the above data to predict the energy demands typically over the next 24 hours and schedule an optimum deployment of the available energy sources, conversion devices and storage to meet the occupants' needs while minimising exergy loss.

The rest of this chapter provides an explanation of how these functions may be realised – to arrive at solutions has involved several innovations which are the subject of patent applications. Despite the apparent complexity of this list, it can be achieved with a limited set of sensors collecting data on temperatures and energy flows, a telecommunications and data processing capability that is well within that provided to a mobile phone, and simple effectors such as relay switches and valves that are found in a conventional heating control system. Novel aspects of the proposed realisation have been tested, either by computer modelling, or within a prototype as described in 3.6 (the hardware and software platform) and the last section of this chapter (the program code structure and test methods).

5.2 Functional Decomposition

Figure 5-1 below illustrates a practical scenario of a household with a CHP boiler providing space heating and domestic hot water, and an immersion heater as an alternative form of hot water heating. Figure 5-2 gives a schematic picture of the functions and data flows within a generalised energy management system that in principle can deal with any combination of energy conversion devices. A high level description of its operation with the configuration of Figure 5-1 is then provided, while subsequent sections cover the detailed techniques employed by individual modules particularly where they are innovative.

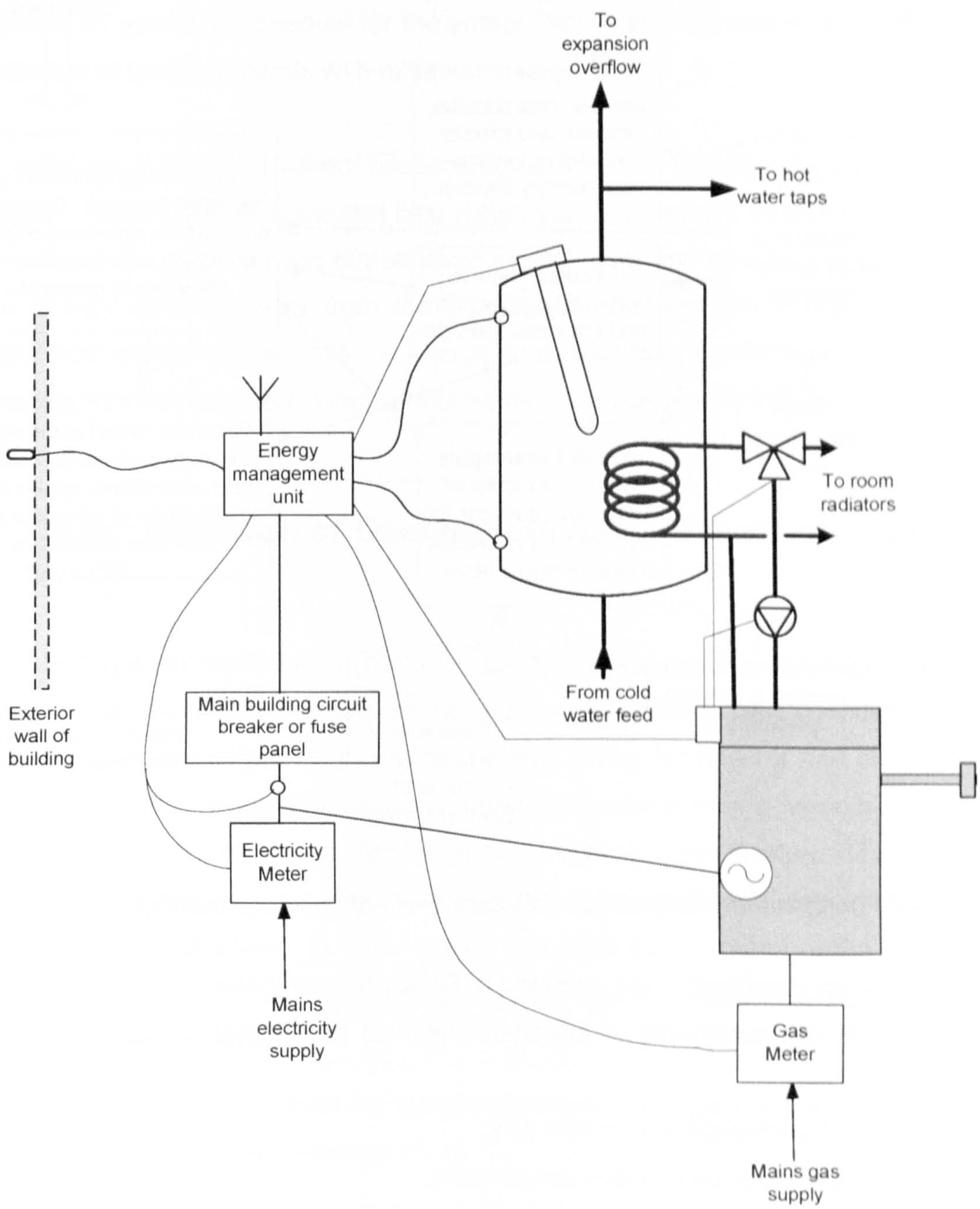

Figure 5-1 Example system controlling micro CHP and immersion heater

Note the test bed has more energy conversion devices than shown in Figure 5-1, while the prototype management system does not implement all the functions of Figure 5-2. So where practical results are provided to illustrate a particular function, they are interpreted where necessary for their relevance to the general concept given in Figure 5-2 and the specific application in Figure 5-1.

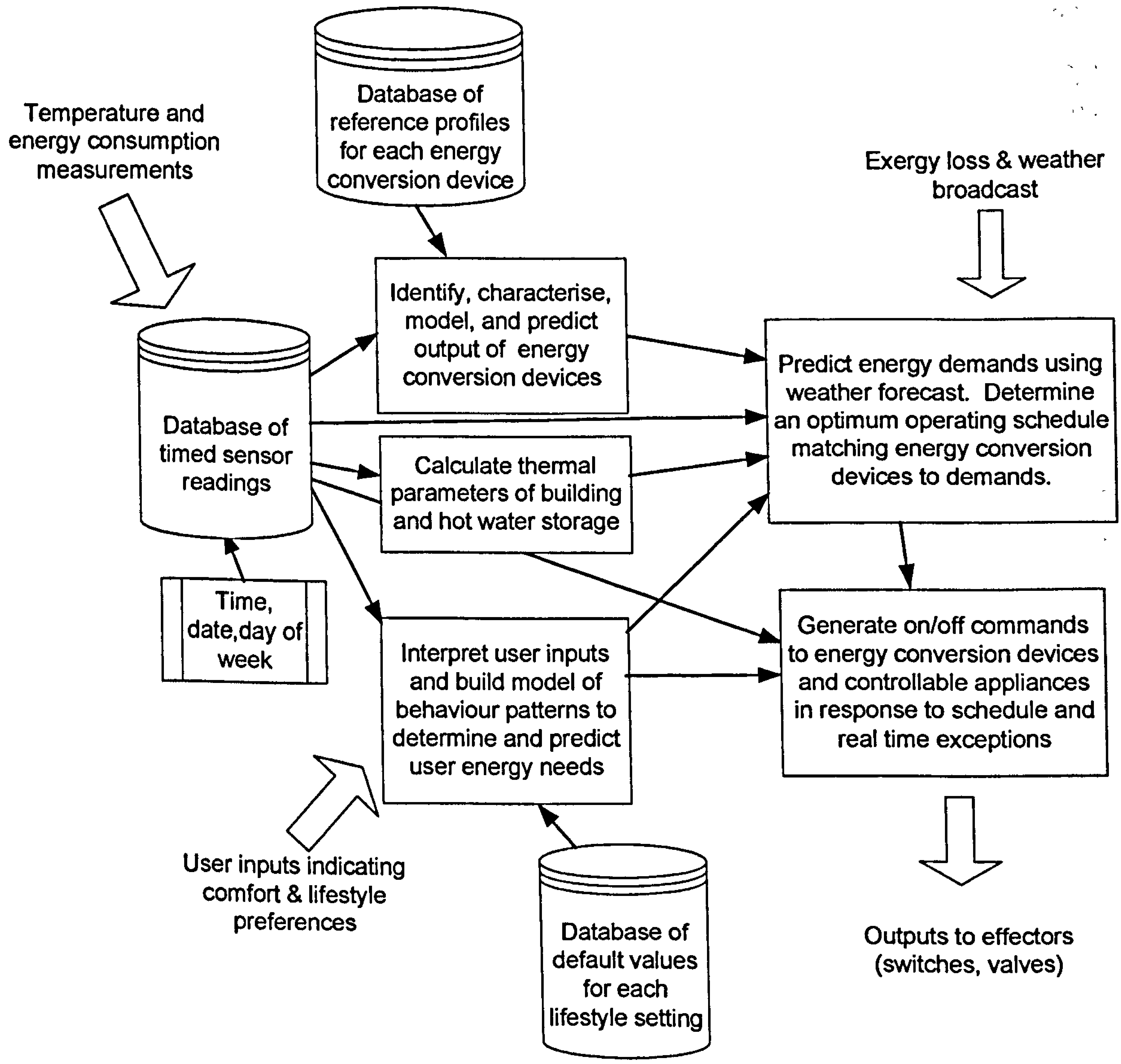

Figure 5-2 Functional decomposition and data flows of universal management system

The sensor inputs employed in the scenario of Figure 5-1 comprise:

- separate measurements of imported electrical power and consumed electrical power;
- the rate of consumption of mains gas;
- internal and external ambient temperature;
- temperature near the top and bottom of the hot water storage tank.

Measurements are taken at intervals and stored with time and date – a 5 minute interval has been used for the prototype, but a more frequent interval would be preferable to capture short term variations more accurately. This data is then processed by the three modules which respectively characterise the energy conversion appliances (in this case the micro CHP, the immersion heater, and the aggregate load from electrical appliances), the building thermal properties, and the occupant behaviour patterns and needs. The parameters from these characterisation processes are then passed to the scheduling and optimisation module. This first makes a prediction of the energy demands for the next 24 hours taking into account a weather forecast (either generated internally from sensor data or acquired with the exergy loss broadcast), and then computes an operating schedule for the energy conversion devices which optimises the satisfaction of these demands with minimum exergy loss.

The optimum schedule is then passed to the module that directly commands the effectors. This module accepts real time inputs from the sensors so that it can operate a conventional set point seeking temperature control loop, and deviate from the schedule when energy demands vary from the prediction – for example if high winds cause greater than expected heat loss. It also accepts real time inputs from the occupants, requesting more or less heat, which should only be needed exceptionally.

5.3 Characterisation of Occupant Behaviour Patterns and Needs

The PhD thesis on modelling of domestic electrical load by Stokes (2005), which was used to model micro CHP exports as discussed in Chapter 3, also provided an insight into a technique for determining occupancy and timing for heating and cooling. That thesis showed how given relatively few parameters concerning a household and their lifestyle, it is possible to accurately model their electricity consumption. This suggested an inverse modelling process should be possible, to derive the household lifestyle from the electricity consumption. In order to fully automate the functions of the programmer shown in Figure 2-4, it is necessary during the heating season to distinguish as a minimum between three states:

1. The occupants of the home are asleep, so require space heating at a temperature between 16-18 °C
2. The occupants are awake and active, so require space heating at a temperature between 19-23 °C

3. The home is temporarily unoccupied, so room temperature can be allowed to fall to a level which allows the occupied temperature to be recovered quickly and avoids dampness - around 12-14 °C is suitable for the UK.

Examination of daily electrical load patterns from the test bed showed that it should be straightforward to identify the time that members of a household get up and go to bed from the rise and fall in electricity consumption that occurs. Figure 5-3 shows a profile from a day (7 December 2007) when the behaviour pattern is particularly easy to diagnose.

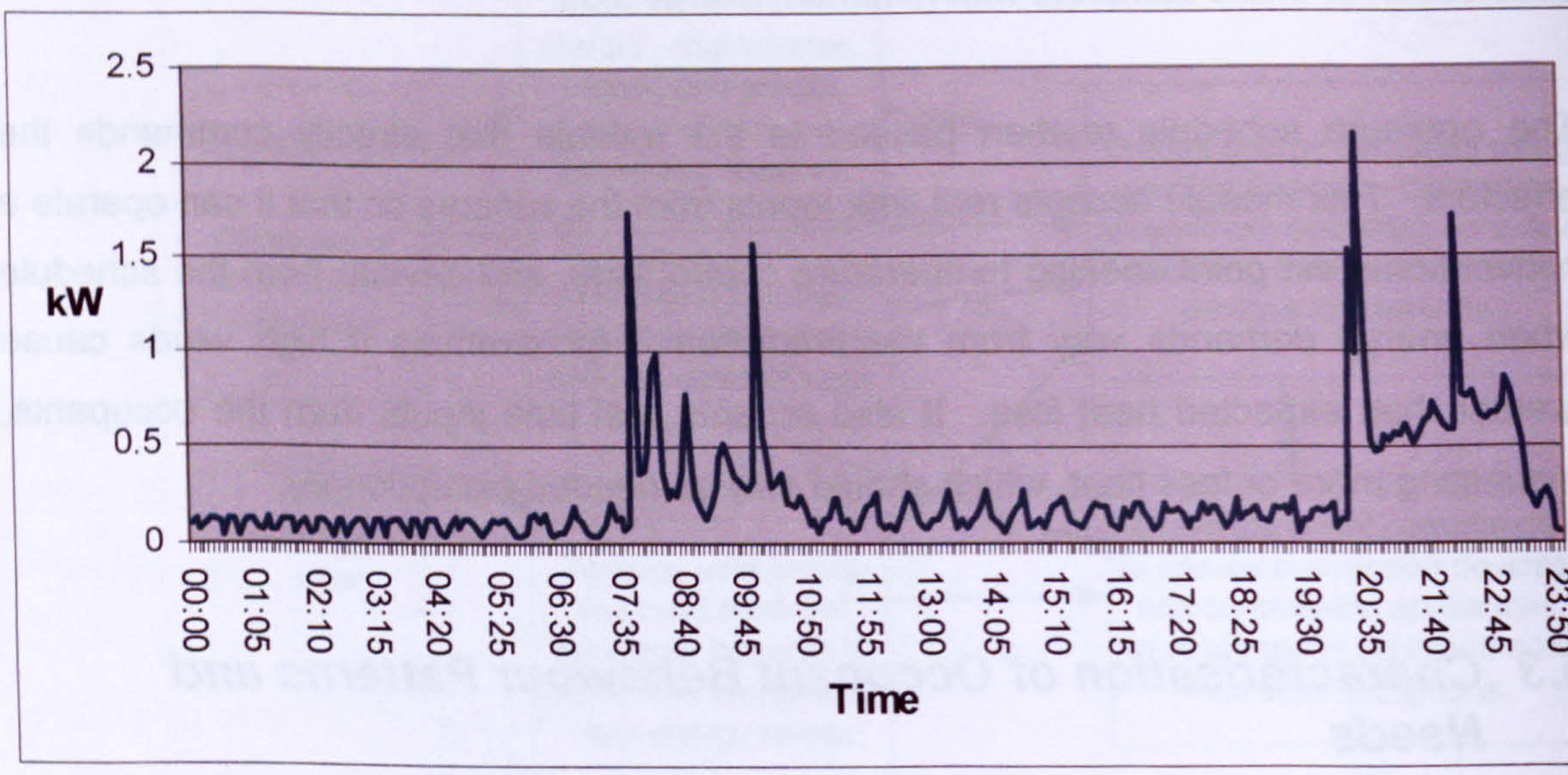

Figure 5-3 Test bed electrical load over 24 hours on 7 January 2007

It can be seen that the kettle went on at 7 a.m, the house was unoccupied from about 10 a.m to 8 p.m, and the occupants went to bed about 11p.m. Between the blocks where lighting and appliances are operating, the load falls back to the cyclic consumption from the fridge and freezer.

The technique developed for the prototype energy management system uses the power level to identify which of the three occupant states should apply. To distinguish between "occupants asleep" and "occupants absent" it is necessary to have prior knowledge that they usually go to sleep between late evening and early morning following a period of high electrical load. This information is obtained by a once-only selection from a shortlist, performed by (or for) the user, of a lifestyle model that is recognisable as the nearest to their behaviour pattern. Table 5.2 lists a minimum set of obvious lifestyle options which will need to be extended and validated through field trials in the development of a practical system. It is envisaged that the option number is entered into the control unit using a thumbwheel switch or similar mechanism.

Option No.	Lifestyle Option	Chosen by:
1	I/We are out of the home weekdays, otherwise at home.	People with "office hours" jobs, families with children at school.
2	I/We are at home most of the time.	Retired people, home workers, invalids, families with young children.
3	I/We do not have a regular time to be at work, asleep or out of the home.	Students, shift workers.

Table 5-1 Lifestyle options for user selection to provide prior probabilities

The identification of occupant state from the electrical load is performed using Bayes' theorem:

$$P(A_1 \mid S) = \frac{P(S \mid A_1)P(A_1)}{P(S \mid A_1)P(A_1) + P(S \mid A_0)P(A_0)} \qquad (5.1)$$

Where:

$P(A_1|S)$ is the probability that one or more of the occupants is present and active (A_1), given that the electrical load sensor has given a positive indication (S). This is the posterior probability-if it exceeds a threshold the active state is identified.

$P(S|A_1)$ is the probability that the electrical load sensor will give a positive indication S, if the occupants are active (A_1). This is the likelihood of the sensor – a range of probabilities is assigned dependent on the level of electrical load.

$P(A_1)$ is the probability that the occupants are present and active. This is the prior probability – initial values are provided for each time of day and day of week dependent on the lifestyle option selected. Its inverse is the probability $P(A_0) = 1-P(A_1)$ that the occupants are not active or absent.

$P(S|A_0)$ is the probability that the electrical load sensor will give a positive indication even when the occupants are not active or absent, i.e. a false indication.

A mean is taken of the posterior probability from equation (5.1) for each time of day with the values for that time from six previous days, and the initial prior probability value given for the selected lifestyle, to give a prior probability for future use. Since some form of weekly pattern can be expected in most lifestyles Mondays are averaged with previous Mondays, Tuesdays with Tuesdays, and so on. The prior probability therefore evolves to reflect the actual behaviour pattern, and time settings in advance for each day can be taken from threshold values of prior probability. This method is also used for hot water timing, based on actual hot water usage patterns instead of electricity load, which can be deduced from tank temperatures as described in the next section.

The results from the prototype shown in Figure 5-4 illustrate how the prior probability evolves in use to capture consistent occupant behaviour. On start up Option 2 was selected as a lifestyle which provides an initial set of prior probabilities that are constant between 08:00 and 22:00. However the occupants were regularly out of the house during daytime on Mondays resulting in development of the prior probabilities shown after 10 weeks operation. The heating times are derived at $P(A_1)$ = 0.6 giving 06:40-08:10 and 15:35-22:45.

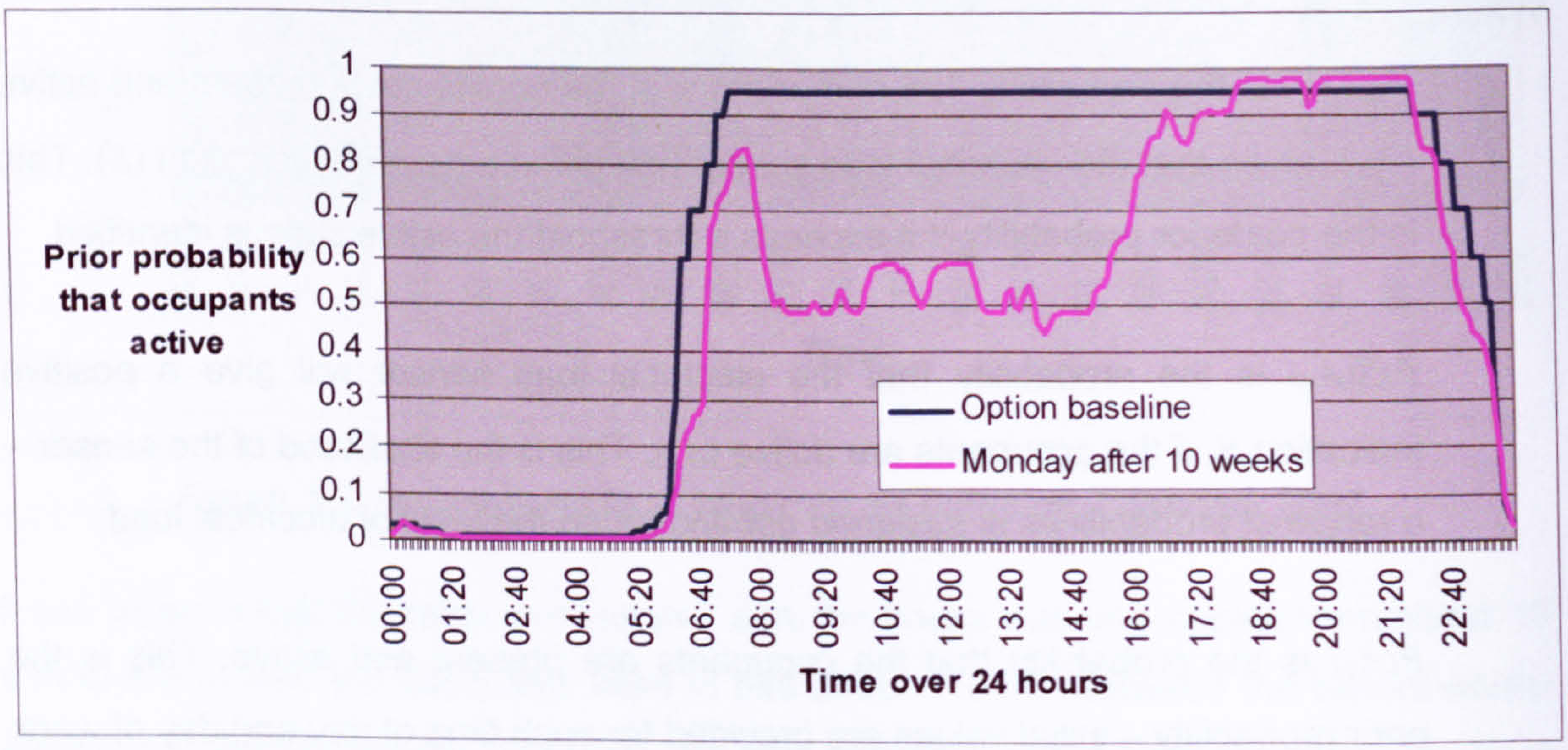

Figure 5-4 Convergence of prior probability on actual occupant behaviour

5.4 Temperature Preferences and Tolerance

The concept of a "lifestyle setting" as illustrated in Table 5.1 provides an opportunity to capture the information needed to determine room temperature preference, by adding an option to the lifestyle description where the user selects one of:

- I/We like our home cooler than the typical level.
- I/We like our home at a normal warm level.

* I/We like our home to be warmer than the typical level.

This phrase could either be included in the lifestyle description, turning the 3 options in Table 5.1 into 9, or it could be a secondary selection. Clearly the exact choice of wording is quite important, and would require quite a lot of field testing, but the intention is to allow exceptional users to identify themselves, such as those with ill health (or babies) who really need quite a high room temperature, and those highlighted in 2.6.4 who prefer a cool home even at a slight risk to their health.

With the selected combination of lifestyle and temperature preference as a basis, the techniques for room temperature setting and variation described in 4.7.2 can be brought to bear. The control system starts with a central temperature of 20°C for the "awake and active" occupancy state, which is consistent with the findings of comfort perception by Humphreys and Nicol (2002b), and then applies a set of adjustments, each determined according to the value of one of the available parameters. This is in effect a similar multivariate process as that embodied in ISO 7730 (ISO, 2005), but adapted to make use of the available information. The parameters and adjustment ranges are:

* The temperature preference setting (-1°C for cooler, +1.5°C for warmer – derived from the spread of comfort perception found by Humphreys and Nicol).
* External temperature (in accordance with Figure 4-8).
* Lifestyle setting which applies a temperature adjustment during the day in accordance with ISO 7730 for expected metabolic rate (-1 °C for moderate activity such as preparing to go to work, +2 °C for a relaxed sedentary state). Clothing insulation of 1.2 ISO 7730 units is assumed – this is reasonably warm interior clothing such as a light jumper.

The prototype applies these adjustments to the central temperature by simple addition. Clearly this is less than optimal – a more sophisticated polynomial equation for temperature would be preferred based on data derived from field trials. This would facilitate introduction of other adjustment parameters, in particular:

* External wind speed – this affects air infiltration into the building and hence perception of comfort. ISO 7730 gives an adjustment for draughts which could be applied. The energy management system could estimate wind speed from heat loss rate and external temperature. Alternatively it could be provided with a weather forecast that includes this data.

- Insolation – this improves perception of comfort by warming rooms with a favourable aspect. This could be detected where there is a solar energy capture device, or obtained via a weather forecast.

So through this method the system arrives at a "best guess" of the user's current preferred temperature. A tolerance range is also required – it is proposed (and implemented in the prototype) that minimum values are ± 0.3 °C, to provide a workable engineering tolerance for the measurement accuracy of low cost temperature sensors, and a hysteresis band for satisfactory control of heating appliances such as micro CHP units which need sustained running rather than frequent on/off cycling. The typical bimetallic strip sensors in current use have a wider measurement tolerance and hysteresis band – about ± 1 °C. In addition to the engineering tolerance of ± 0.3 °C, it is proposed that an upward allowance of +0.5 °C should be permitted to the system where such an adjustment is calculated to reduce exergy loss (for example as shown in Chapter 4 for despatch of micro CHP to reduce the early evening electricity demand peak). Where metabolic rate adjustments imply a requirement for an upward movement of temperature during the day this allowance is reduced or eliminated accordingly. Overall these tolerances should give a perception of temperature stability at least as good as current domestic systems while allowing the necessary variation needed for exergy loss minimisation.

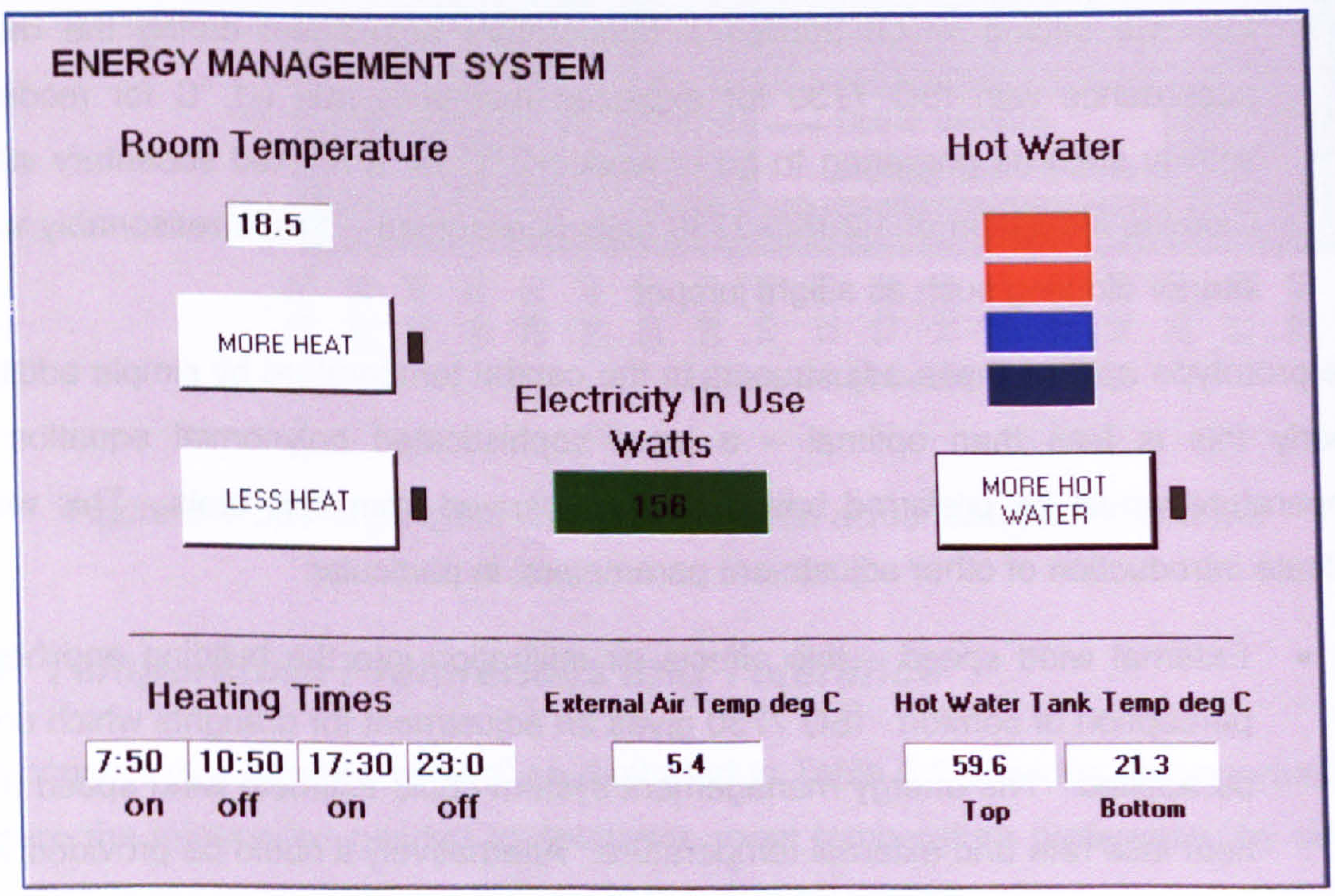

Figure 5-5 User interface of prototype

The research considered in 4.7.2 highlights the importance of "adaptive opportunity". This is provided in the prototype by two buttons labelled "More Heat" and "Less Heat" as shown in the screen shot of Figure 5-5. The objective behind them is to give a user the ability to inform the system of their needs, while denying absolute control over the temperature setting to avoid the problems identified in 2.6.4. The functional operation is therefore much more complex than a conventional thermostat. If the "More Heat" button is pressed, the following logic applies:

- A placebo indicator lights with a 5 minute timeout to show the system has taken notice of the input.
- If the system is currently in the "unoccupied" or "asleep" states as defined in 5.3, it changes to the "active" state and heating to the applicable room temperature commences. Occupancy is also recognised within the Bayesian behaviour model.
- If the system is in the active state and heating is in progress but has not reached the target room temperature set point, no action is taken.
- If the system is at the target room temperature, then a temporary increment is applied to the room temperature set point that is sufficient to provide approximately an hour's running of the heating system taking into account the thermal capacity of the building. A small semi-permanent increment (0.2 °C) is also added to the set point for that hour – in effect this is another adjustment applied along with the other adjustment parameters.

If the "Less Heat" button is pressed, the logic is:

- Again a placebo indicator lights with a 5 minute timeout to show the system has taken notice of the input.
- If the system is currently in the "unoccupied" state no action is taken.
- If the system is currently in the "asleep" or "active" state, a temporary decrement is applied to the room temperature set point that is sufficient to provide an hour's cessation of the heating system, if it is on at the time. A small semi-permanent decrement (0.2 °C) is also subtracted from the set point for that hour.

To ensure that the aggregate effect of the automatic and manual adjustments does not lead to an excessively high or low set point for the "active" occupancy state, bounding limits of 17°C and 25°C are applied by the system. To avoid adjustments that are applied to meet temporary circumstances causing long term inefficiency each semi-permanent variation is "aged off" after two months, the concept being that by then seasonal weather conditions will have moved on.

Practical operation of an automatically varying room temperature set point by the prototype is illustrated in Figure 5-6, for the same day as shown in Figure 5-4. The three levels reflecting the three identified occupant states are clear – the set point rises prior to the required heating times to allow warming up time. The small rises in set point during the afternoon and evening were entered manually using the "More Heat" button. It is unlikely that these occupants would have turned off their heating during the day on Mondays if they were using a conventional programmer such as that shown in Figure 2-8, because their normal lifestyle pattern is to be mainly at home in accordance with their selection of Option 2. The dip in room temperature during the unoccupied state shows that an energy saving has been achieved, although in the case of this prototype installation it is modest (4.4 kWh) because of the high thermal capacity (16 kWh/ °C) of the house.

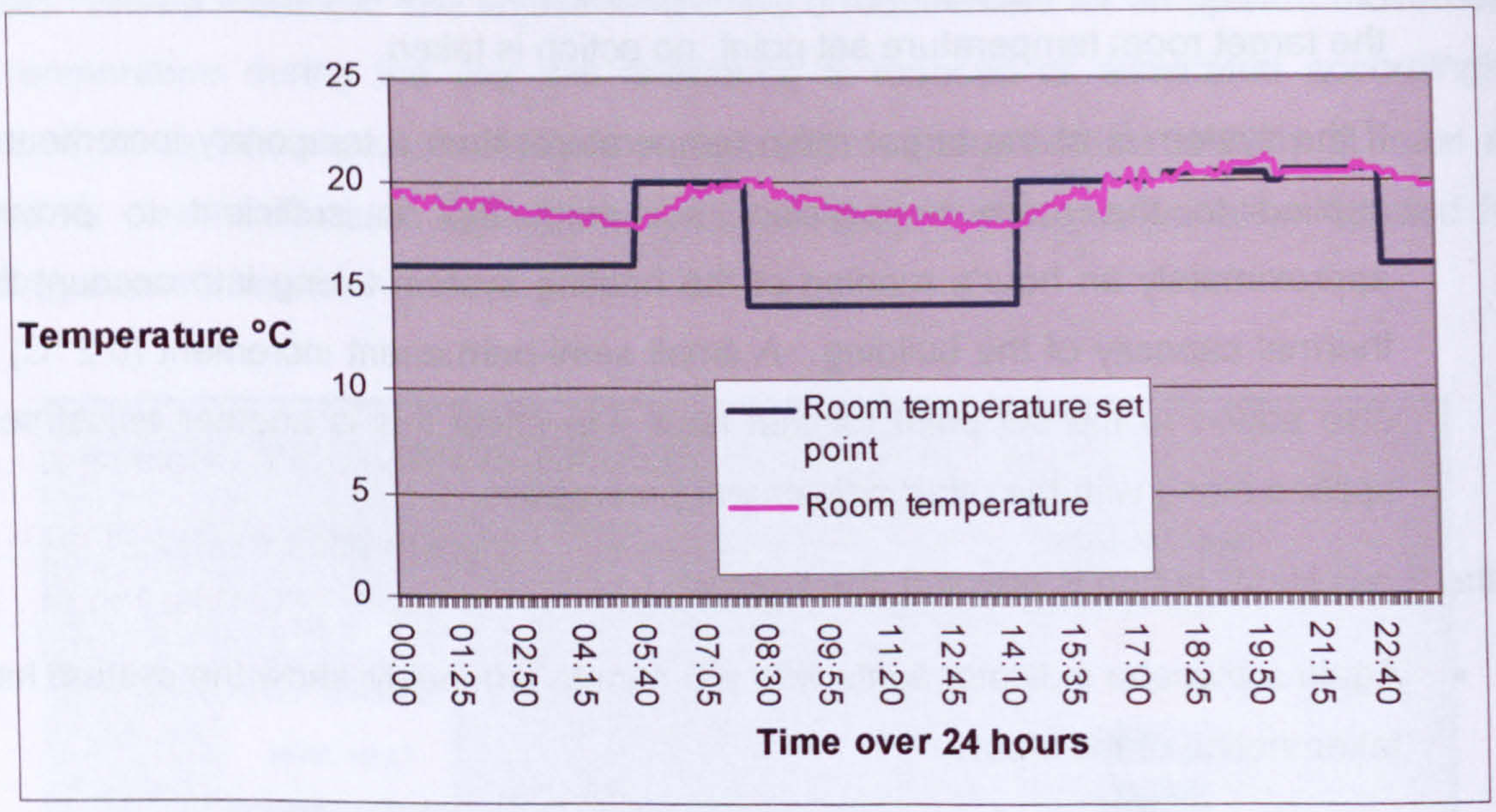

Figure 5-6 Variation of room temperature set point, and resulting room temperature

The problem in setting temperatures for domestic hot water is rather different. Since the end use of hot water generally involves mixing it with cold water to the user's satisfaction, the acceptable temperature range is bounded by a lower level that is adequately above body temperature so that it feels hot (about 40 °C) and an upper level between 50 °C and 60 °C that avoids scalding[10]. There is also a constraint as identified in Chapter 2 that 60 °C should be achieved regularly in the hot water storage tank as an anti-bacterial measure – this is usually reconciled with the scalding limit using a

[10] A 50 °C upper level is preferred if any members of the household (such as young children) are likely to use the hot water direct from a tap.

thermostatic mixing valve on the outlet pipe from the tank. So the energy management system can work with quite a large temperature range, and it can predict the timing of hot water use using the method described in 5.3, but to make use of the storage capacity of the tank it also needs to know what volume of water in this temperature range will be drawn off. With this information it can discriminate, for example, between a household with a single occupant who takes a short shower at a given time, and a household with several small children who are all bathed at the same time and thereby consume a lot of hot water.

By equipping the hot water tank with two temperature sensors as shown in Figure 5-1 instead of the single sensor currently employed in most homes, all the necessary information on hot water use can be collected. The additional sensor is placed near the base of the tank. Figure 5-7 illustrates a typical pattern from the test bed of temperatures from these sensors, on a day when there was a modest level of insolation so limited heating from the solar panel, and the micro CHP was scheduled to bring the tank up to temperature at 7 p.m. when there was no further prospect of solar energy collection.

It can be seen that when hot water is drawn off, the temperature at the base of the tank falls sharply as cold water is drawn in. This event alone is sufficient to signal hot water use and occupancy for the purpose of timing extraction as described in 5.3. Once draw-off ceases the tank base temperature then rises as the turbulence of the incoming water dissipates and the normal temperature stratification of the tank is recovered. Depending on the volume of water drawn off, there will also be a temperature fall at the top of the tank, although this drop is small until the volume of hot water in the upper part of the tank from the previous heating cycle is consumed.

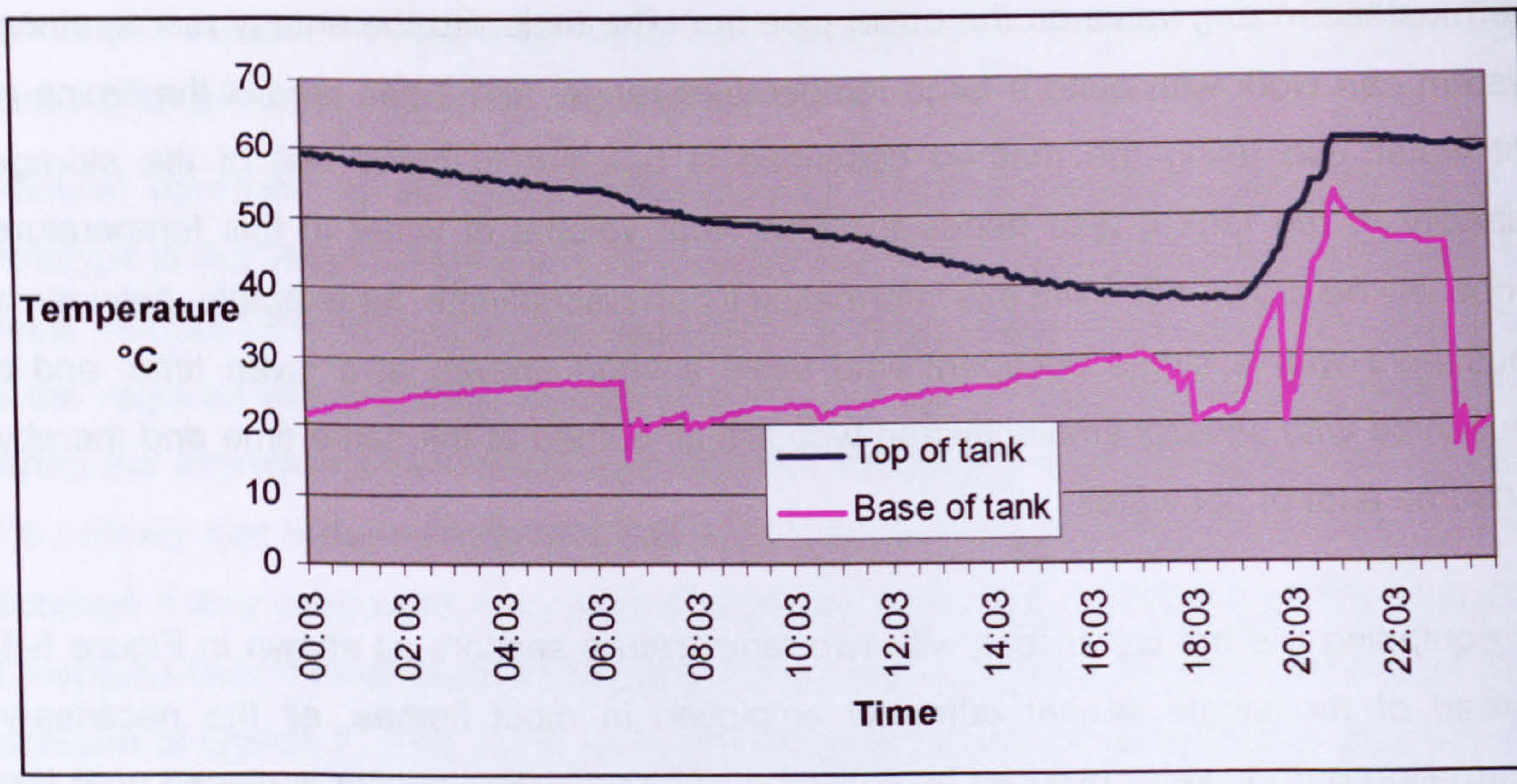

Figure 5-7 Hot water tank temperatures

By comparing the temperature of the tank base sensor before and after the draw-off event, the proportion of the tank volume that was drawn off can be estimated, and also the proportion of the volume that remains that is within the useful temperature range. To do this the energy management system models the contents of the tank as comprising an upper volume V_t above the heating coil or element that is all at the temperature T_t indicated by the upper sensor, and a lower volume V_b that is linearly stratified in temperature between that of the upper volume and that (T_f) of the cold feed water. V_t is assumed (from the standardised dimensions of UK hot water tanks) to be 66% of the total volume where the water is heated by the heat exchanger coil, and 50% for the electrical immersion heater[11]. A draw-off volume V_d can then be estimated by the change in temperature of the lower sensor ΔT_b it causes. The lowest temperature seen immediately after draw off is taken as T_f (for example that seen at 06:30 in Figure 5-7) while ΔT_b is measured using the stabilised T_b (as seen at 07:30 in Figure 5-7). V_d is then taken as:

$$V_d = V_b \Delta T_b / (T_t - T_f) \tag{5.2}$$

By integrating these values of V_d from the time immediately after full heating of the tank has been achieved (21:00 in Figure 5-7) the progressive consumption of hot water can be monitored. The method is not very accurate, but results from the test bed indicate

[11] Where only electrical water heating is provided, a second element is usually installed so V_t can be taken as 75%.

that it is fit for the purpose of identifying the relative volumes of each draw off event. Figure 5-8 illustrates the method in practice.

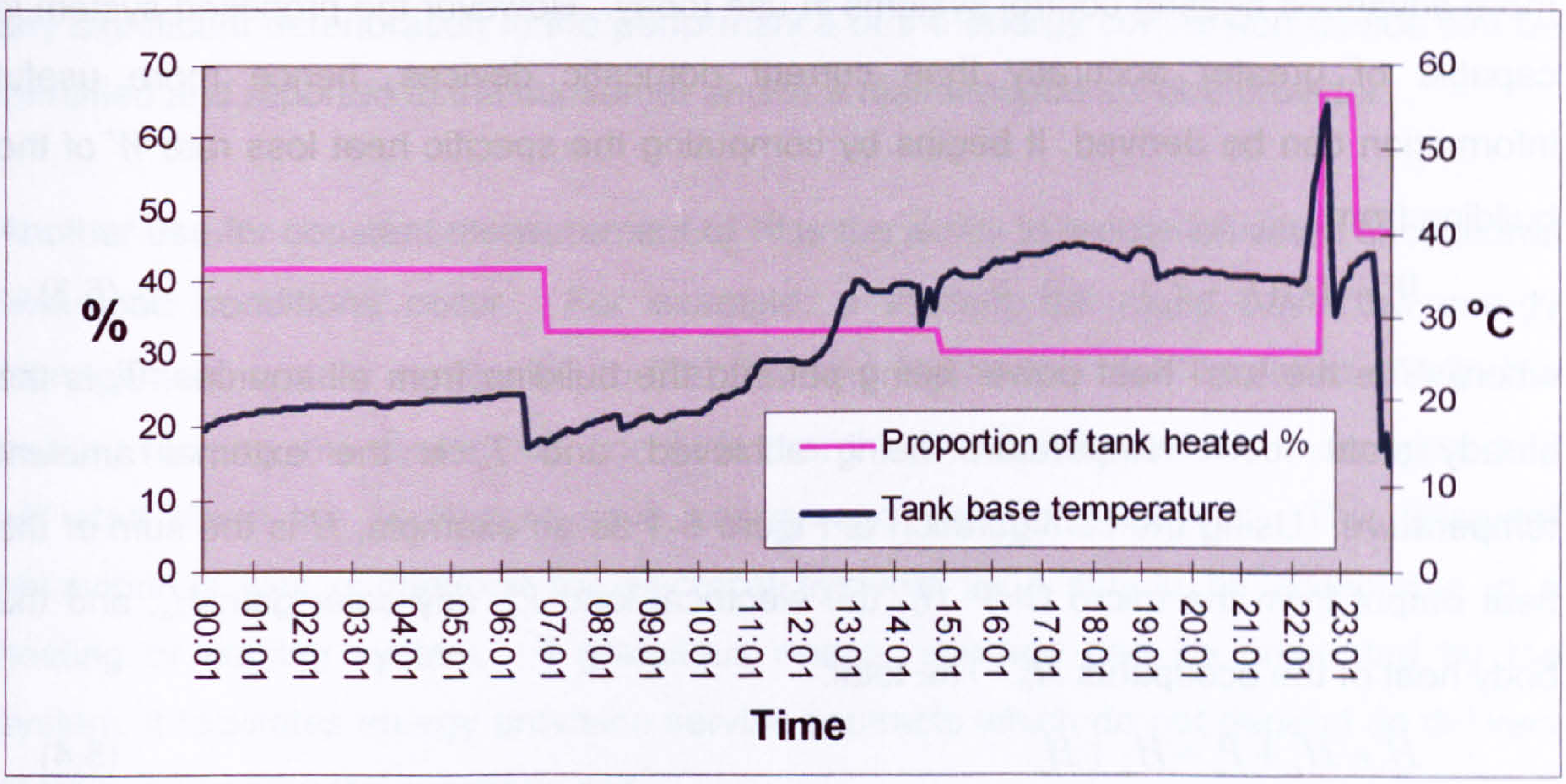

Figure 5-8 Hot water tank usage measurement

The downward steps in the plot of heated volume at 07:00, 15:00, and 23:00 show where hot water use has been recognised and quantified by the system. The upward step at 22:30 reflects the heating of the tank by the micro CHP, as can also be seen in the temperature spike. Tank heating has been timed by the system to take place shortly before the major hot water use of the day when the occupants take a shower.

Having provided a basis for automating the supply of hot water, some means to allow the user to actively express their needs to the system is required. The display shown in Figure 5-5 indicates the temperature of the tank contents with a bar graph having a segment for each quarter of the tank. Temperatures over 55 °C are indicated by red, 40 °C - 55 °C by pink, 30 °C - 40 °C by light blue, below 30 °C by dark blue. While this presentation is inevitably approximate, over time the users should become accustomed to what it represents for their consumption patterns, and whether or not it is adequate for some immediate use. Depressing the button labelled "More Hot Water" causes heating of the tank to be initiated up to the maximum normal working level. In principle, this should only be needed exceptionally where the user is deviating from their regular consumption pattern – only field trials beyond the scope of the present research can determine to what extent it will be used unnecessarily.

5.5 Characterisation of Building Thermal Properties

This function of the energy management system is not innovative, it is found on the more advanced heating control systems in use today. However the proposed system is capable of greater accuracy than current domestic devices, hence more useful information can be derived. It begins by computing the specific heat loss rate W of the building from:

$$W = H/(T_r - T_e) \tag{5.3}$$

where H is the total heat power being put into the building from all sources, T_r is the steady state room temperature being achieved, and T_e is the external ambient temperature. Using the configuration of Figure 5-1 as an example, H is the sum of the heat output from the micro CHP H_c, the electrical load P_e, any solar gain H_s, and the body heat of the occupants H_o. The total:

$$H = H_c + P_e + H_s + H_o \tag{5.4}$$

can be most accurately evaluated on evenings or early mornings when the heating is off, so H_c and H_s are zero, and H_o can be estimated from $H_o = kO$ where O is the occupancy as determined using the techniques described in the next section, and k is an average human heat output at rest (typically 200W, but it could be adjusted from the lifestyle factor discussed later). Because of the high evening electrical load and fairly good insulation that are now found in most homes, opportunities to calculate W accurately in this way should be fairly frequent.

The value of W will of course vary depending on weather conditions – it will be higher in rain or high wind. It may also vary for a terrace or semi-detached house when heat gains or losses from an adjacent property vary. So over time the system will compute an average value for W, and hold a range of values where a correlation between weather as known to the system, and W, is recognised. Once a value for W is established then using equations 5.3 and 5.4 on an evening when heating is required H_c can be determined. By comparing H_c with the rate at which gas (or other fuel) is consumed the efficiency of the energy conversion device performing the heating can be calculated. For our micro CHP example the electrical output P_o must be taken into account, so the First Law efficiency is given by:

$$\eta = (H_c + P_o)/(4.2K\frac{\partial V}{\partial t}) \tag{5.5}$$

where K is the volume unit calorific value of the fuel and $\partial V / \partial t$ is the rate of consumption. Clearly exergy loss can also be calculated for use by the optimisation process, and a further advantage of calculating efficiency on a sustained basis is that any significant deterioration in the performance of the energy conversion device can be identified and reported to the consumer and/or a maintenance service provider.

Another use for constant measurement of W is the ability to recognise when exceptional heat load conditions occur. For example, a student flat might have the energy management system configured so that if a very high value of W is detected with the heating running, the system will conclude that they have left windows wide open, and will shut down the heating to save energy and carbon emissions. This "tripping" behaviour is well understood for electrical systems so it should be acceptable in a heating or cooling system. If gratuitous energy wastage can be prevented by the system, it facilitates energy provision service contracts which do not depend on delivery of kWh, by limiting the supplier's risk.

The other key building thermal parameter to be computed is the thermal capacity C. This is readily obtained by the system from the heat balance during the overnight decline in internal temperature, using:

$$W(T_r - T_e) = C \partial T_r / \partial t + H \tag{5.6}$$

Often H will just comprise heat from a small electrical load drawn by refrigeration appliances, and an allowance for the body heat of the sleeping occupants, permitting C to be calculated with reasonable accuracy for typical UK homes of brick or concrete block construction.

If the building has a thermal store such as a hot water tank, then the heat loss rate and thermal capacity of that are also valuable parameters for optimisation and scheduling. They can be obtained using the above methods and equations, *mutatis mutandis*. The only difficulty arises where there is no electrical heater (such as an immersion heater) to provide an accurate measurement of heat input. In that case the efficiency of any combustion-based energy conversion device used to heat the store will have to be extrapolated from its efficiency in a space heating role. Where electrically heated thermal storage heaters are used their thermal parameters can be determined precisely using these methods.

5.6 *Characterisation of Energy Conversion Devices*

The identification and characterisation of any energy conversion device that is reasonably likely to be present can be performed using pattern recognition and correlation techniques on the time varying sensor measurements obtained from its energy inputs and outputs. Taking the immersion heater from Figure 5-1 as a simple example, the electrical power it consumes as detected by the electrical load sensor is correlated with a rise in the temperature recorded by the upper tank temperature sensor as shown in Figure 5-9 below.

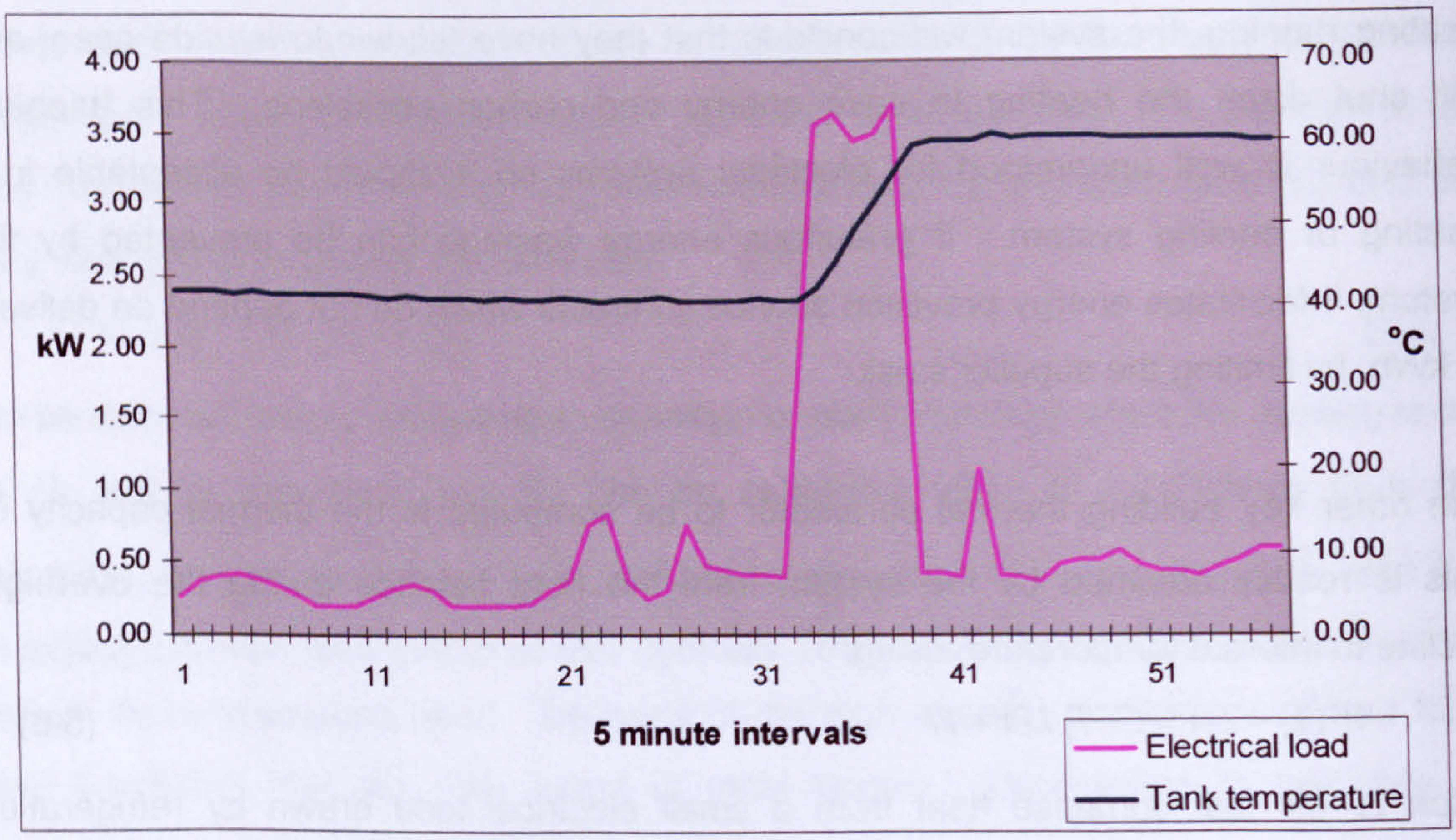

Figure 5-9 Hot water tank temperature and total electrical load

The energy management system will be responsible for switching on the immersion heater, so it can measure the electrical load that it presents, and from the rate of rise of the tank temperature an estimate of the tank volume can be obtained. The heated volume V_t is given by:

$$V_t = Q / 4.2\Delta T \tag{5.7}$$

where Q is the energy input and ΔT the temperature rise in the same interval. This ignores heat losses during the period the immersion heater is operating – Figure 5-9 shows these are quite low as the rate of fall of temperature with no energy input is about 0.5°C per hour. The data in Figure 5.3 indicate a heated volume of 54 litres. Using the same assumptions on the proportion of tank volume that is heated as employed in 5.4, the tank volume is estimated at 108 litres. The system then rounds this to the nearest standard tank size of 100 litres.

With this information and the usage model from 5.4, the energy management system can compute when the immersion heater should be switched on to deliver the desired set point at a specific time, taking into account the exergy loss associated with electricity at different times as conveyed in the broadcast described in Chapter 4. Using the immersion heater as a benchmark, it can also evaluate the water heating performance of other energy conversion devices such as the micro CHP in Figure 5-1. By measuring the gas consumed when the micro CHP is purely heating domestic hot water, and given a stored value for the calorific value of the gas, the efficiency (in terms of exergy loss) of the micro CHP in this role can be calculated. Results from the test bed show that the efficiency is sometimes poor – Figure 5-10 below shows the micro CHP heating water in the early evening after a reasonably sunny day has allowed the solar panel to pre-heat the water to 52 °C. The micro CHP has a hot water set point of 60 °C, but because of minimum running time constraints it overshoots driving the hot water up to nearly 70 °C. The left hand Y axis shows the calorific value of the gas input expressed as kW for comparison with Figure 5-8. The total chemical energy input in this episode is 6.3kWh, which was translated into 1.7kWh of heat energy in the water tank, and also 0.4kWh of electrical energy. Of that 1.7kWh of heat energy about 0.8kWh in the overshoot was not needed. So the overall First Law efficiency was about 21% - clearly it would have been much more efficient to employ the immersion heater even allowing for the losses in electricity generation and distribution.

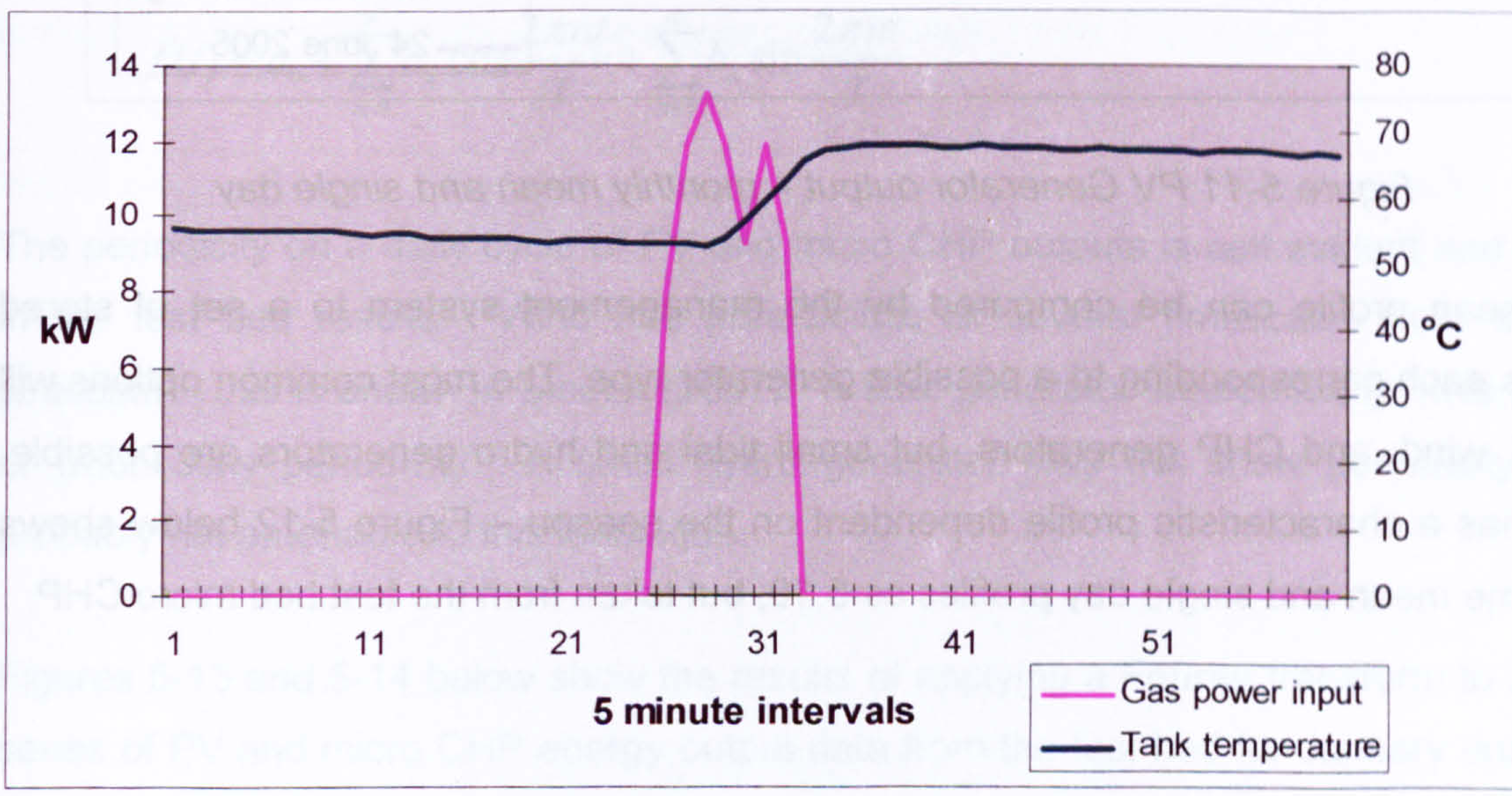

Figure 5-10 Hot water tank temperature and gas input power

It is also possible for the system to identify and characterise any form of domestic electricity generator. The presence of a generator will be visible to the management system because there will be a difference between the measurements of electrical load and of electrical power imported from the mains. The import may of course become negative implying export. So the instantaneous generator power P_o will be given by:

$$P_o = P_d - P_m \tag{5.8}$$

where P_d is the load and P_m the import power. The time varying profile of P_o is characteristic of the type of generator. For example, the output of a PV generator has an upper limit set by the pattern of solar radiation. By summing the value of P_o for each time of day over a period in the range 7-30 days the management system can obtain a mean daily profile for P_o which does not contain random minute-to-minute variations. The mean profile obtained from the test bed for June 2005 is shown in Figure 5-11, compared to a single day.

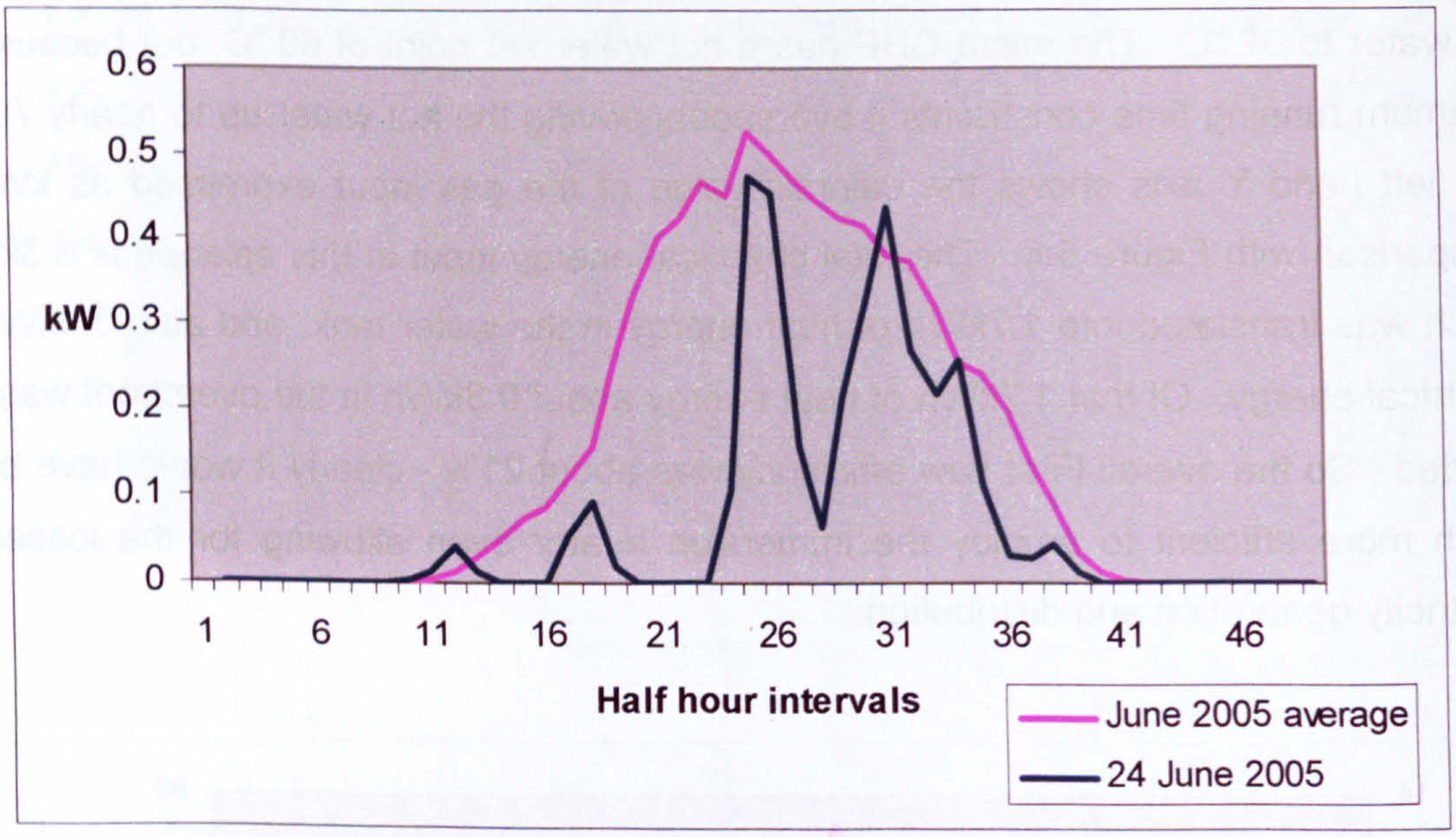

Figure 5-11 PV Generator output – monthly mean and single day

This mean profile can be compared by the management system to a set of stored profiles each corresponding to a possible generator type. The most common options will be PV, wind, and CHP generators, but small tidal and hydro generators are possible. Each has a characteristic profile dependent on the season – Figure 5-12 below shows the same mean and single day profiles as 5.10, but taken from the test bed micro CHP.

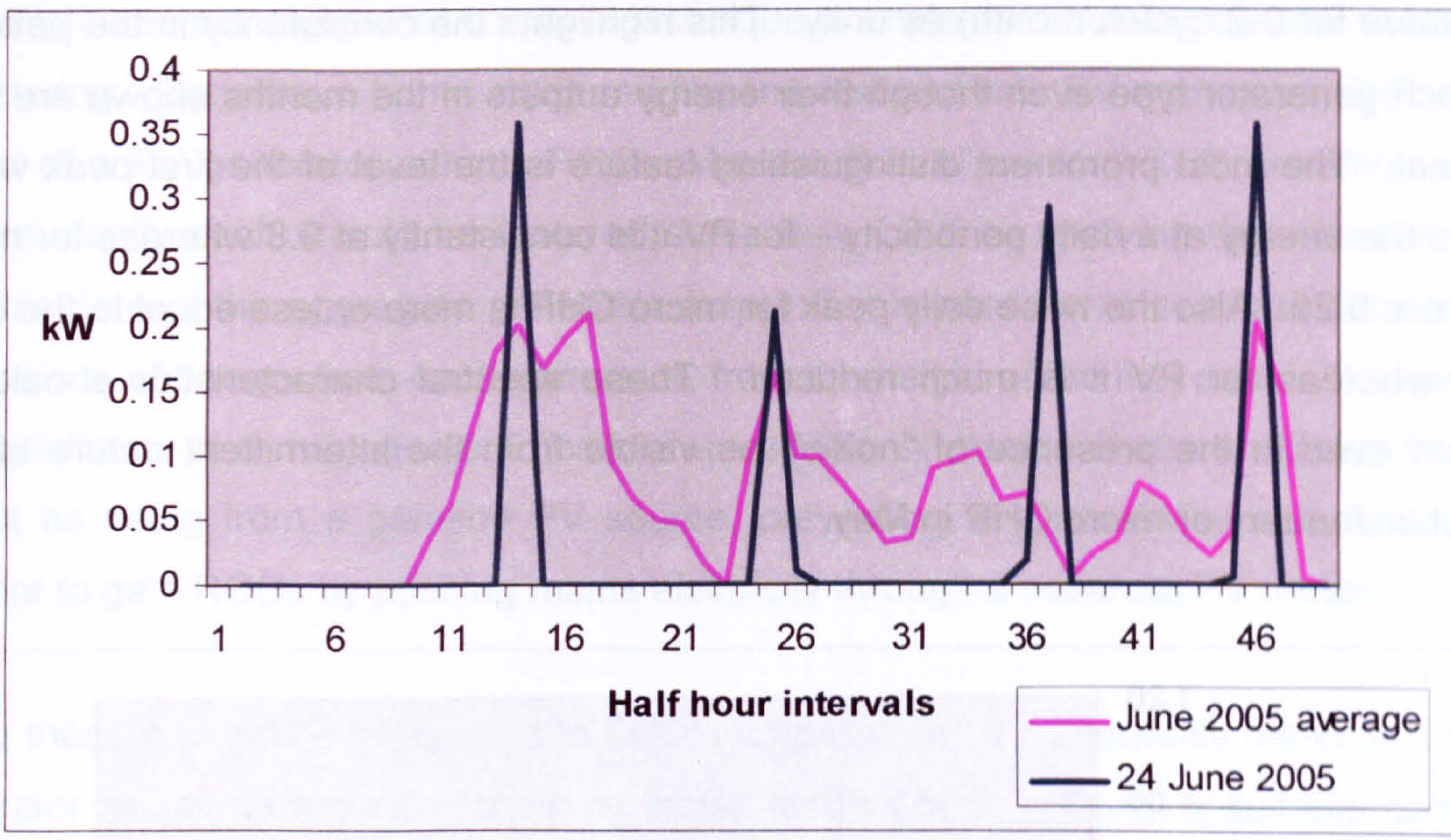

Figure 5-12 Micro CHP Generator output-monthly mean and single day

Clearly a different household might have fewer or more peaks resulting from hot water usage during summer. To improve the robustness of pattern matching, a frequency domain comparison can be employed as well as time domain. A Fourier series representation of any periodic function is possible provided that $\int f(t)dt$ is finite over a complete period and $f(t)$ is continuous. If these are satisfied the function can be represented as:

$$f(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos\frac{2\pi nt}{T} + \sum_{n=1}^{\infty} b_n \sin\frac{2\pi nt}{T}$$

The periodicity on a daily cycle of PV and micro CHP outputs is self evident and visible in the test bed results. Wind has periodicities at several timescales from daily to seasonal – this is shown in Sinden (2007). A tidal generator would clearly have a daily or twice daily periodicity. A small hydro generator may not show periodicity so is probably not amenable to this technique.

Figures 5-13 and 5-14 below show the results of applying a Fourier transform to 30-day series of PV and micro CHP energy output data from the test bed for January and May. This resolves the a_n and b_n vectors at each frequency into a single value. The Y axis, which would otherwise show energy spectral density values that are difficult to interpret[12], has been normalised by taking the first frequency axis point for each month

[12] They would be watts/radian for half of the energy in the series because the other half is translated into negative frequency values which are not shown in a conventional one-sided plot. Also the series is infinite so some of the energy is not shown.

(the value for 0-2 cycles/month) as unity. This highlights the consistency in the patterns for each generator type even though their energy outputs in the months shown are very different. The most prominent distinguishing feature is the level of the first peak which shows the energy at a daily periodicity – for PV it is consistently at 0.8 whereas for micro CHP it is 0.25. Also the twice daily peak for micro CHP is more or less equal to the daily peak whereas for PV it is much reduced. These spectral characteristics should be reliable even in the presence of "noise", as visible from the intermittent nature of PV output in January or micro CHP in May.

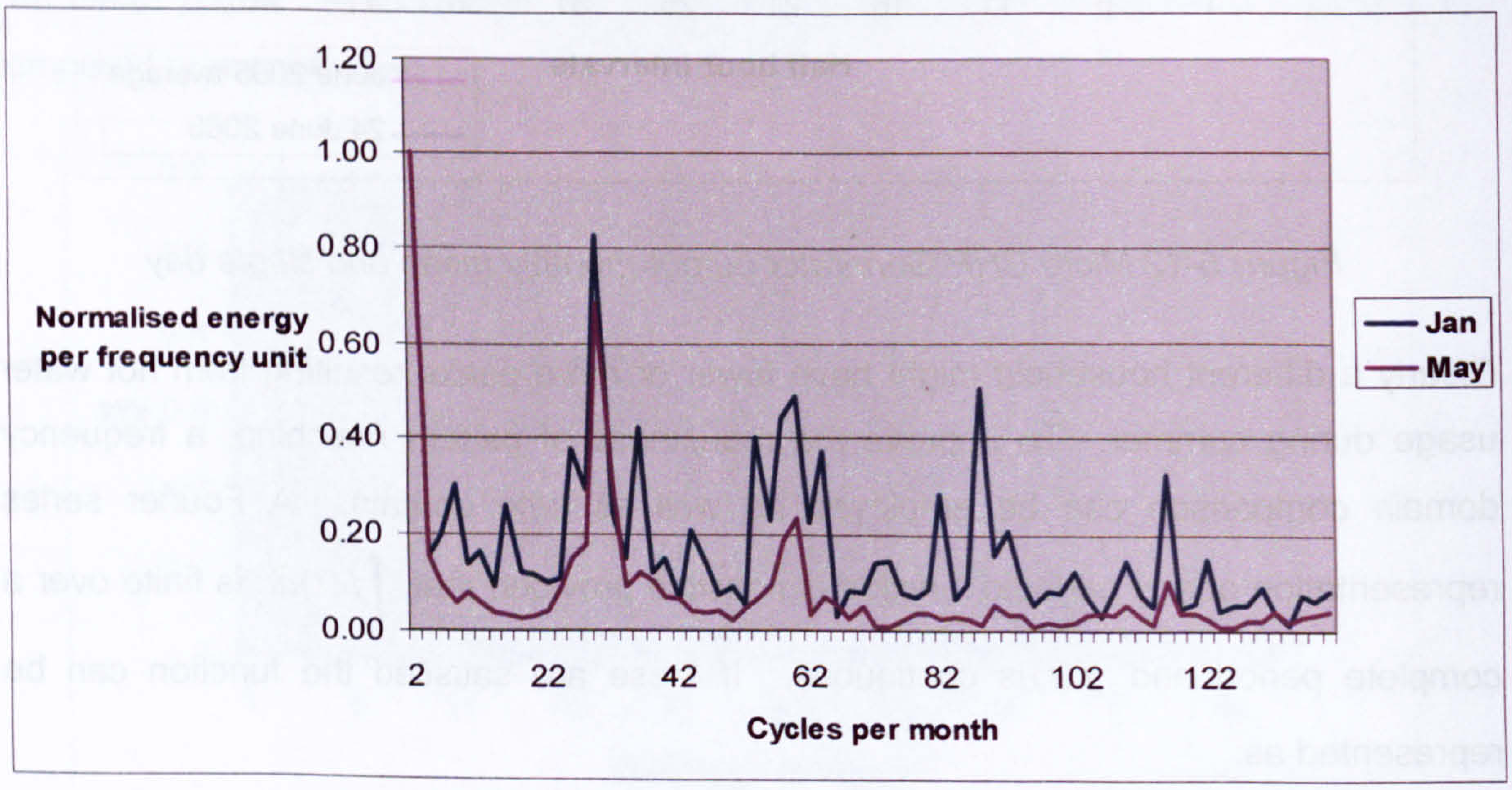

Figure 5-13 Fourier transform of PV output series

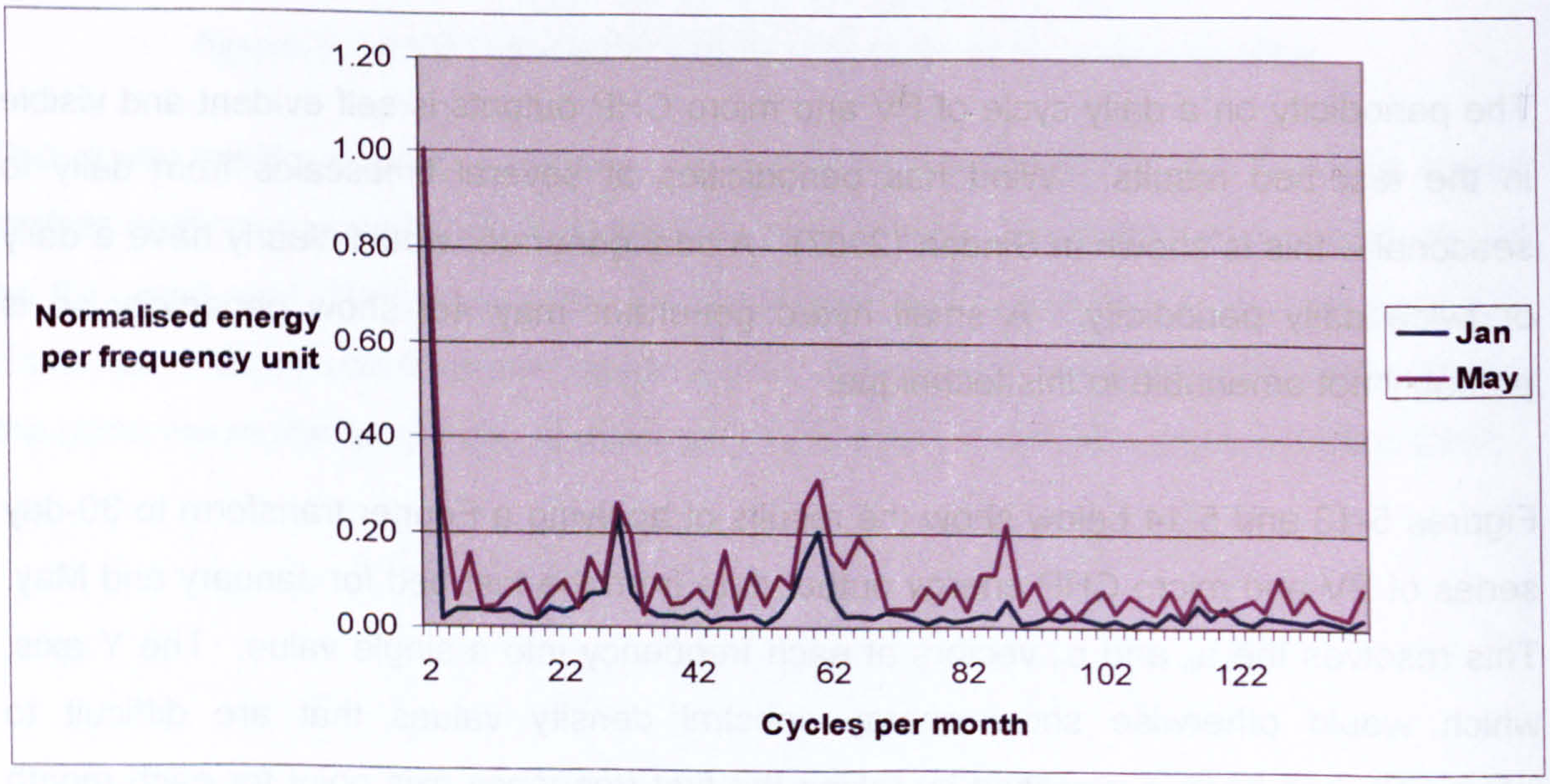

Figure 5-14 Fourier transform of micro CHP output series

This might seem a somewhat complex technique to implement but its potential value lies in metering. Consider a home equipped like the test bed with PV and micro CHP. The output of a PV generator attracts ROCs whereas that of a micro CHP generator does not, so ideally each should be metered separately. But by applying this analysis to a month's data of the aggregate generator output G it is possible to estimate the relative proportions of energy from each generator, from the height of the first peak. This avoids the installation and management costs of an additional meter. It also validates the PV output as being from a genuine PV source, preventing any possibility of a fraudulent attempt to gain ROCs by pushing mains electricity through a separate PV meter.

Using these methods it is possible to firstly recognise and subsequently meter any local generator simply by recording the time series for P_d and P_m. Given a suitable contract with the energy utility, this should allow the consumer to "plug and play" any generator and be rewarded for the renewable generation and/or export that it delivers. The amount of signal processing applied to the time series can be commensurate with the accuracy of metering required – currently for domestic scale generation ROCs are awarded on annual output rounded to the nearest MWh so do not demand great accuracy. The technique as applied to renewable generators is the subject of a patent application (DMU, 2007a).

The patterns and correlations that should allow recognition of most common forms of domestic energy conversion device are summarised in Table 5-2 below.

Sensor measurements	**Patterns observed**	**Energy conversion device identified and modelled**
Hot water tank temperature, electrical load	Rising water temperature on command correlated with electrical load in range 1 – 10kW	Electric immersion heater
Hot water tank temperature	Rising water temperature correlated with reference profile for solar radiation intensity, no correlation with command	Solar water heater
Hot water tank temperature, electrical load, gas consumption	Rising water temperature on command correlated with gas consumption and small electrical load	Gas boiler with electric water pump

Sensor measurements	Patterns observed	Energy conversion device identified and modelled
Hot water flow temperature, gas consumption	Use of hot water correlated with gas consumption.	Combi boiler supplying direct hot water.
Hot water tank temperature, electrical load, metered electrical power, gas consumption	Rising water temperature on command correlated with gas consumption, small electrical load, and difference between electrical load and metered power	Gas combined heat and power (CHP) generator with electric water pump
Internal air temperature, electrical load, gas consumption	Heating effect on command correlated with small electrical load and gas consumption	Gas boiler with electric water pump
Internal air temperature, electrical load, external air temperature	Heating effect on command correlated with small electrical load, heat output decays with time	Heat extraction by fan from storage in a thermal mass
Internal air temperature, electrical load, external air temperature	Cooling effect on command correlated with electrical load, cooling output and electrical load dependent on external temperature.	Air conditioning unit
Internal air temperature, electrical load, external air temperature	Heating effect on command correlated with electrical load, heating output and electrical load dependent on external temperature	Heat pump
Electrical load, electrical power imported from mains	Detection of locally generated electricity with pattern matching profile for wind turbine capacity factor	Micro wind turbine
Electrical load, electrical power imported from mains	Detection of locally generated electricity with pattern matching profile for solar radiation intensity	Solar photovoltaic generator

Table 5-2 Energy conversion device recognition

5.7 External Data Reception and Interchange

The previous sections have focussed on the data processing that the energy management system must perform to derive necessary information. However given the aim to integrate domestic systems with their wider environment, to complete a solution some means must exist to exchange information with the outside world. The Radio Teleswitch system has already been proposed as a medium for delivery of the exergy loss of mains electricity. This could readily be expanded to cover predicted air temperatures, insolation, and wind speeds for each region, allowing precise prediction of energy demands and resources by the management system.

There is also a need for data to be exchanged that are specific to the household. Table 5-3 summarises this with the direction of flow, likely source or destination, and worst-case periodicity (i.e. where a very dynamic relationship is maintained between the energy management system and the environment, such as a microgrid).

Data content	To or from external entity	External entity	Periodicity
Metering values	To	Energy supply company or Ofgem (for ROCs)	Daily
Tariffs	From	Energy supply company	Daily
Energy conversion device performance metrics	To	Appliance maintainer	Monthly and when a fault occurs
Generator shut-off command	From	Distribution network operator	Rarely (when there is a distribution fault)

Table 5-3 Household-specific data flows

There are several possible transmission media for the data flows in Table 5-3, each with their own advantages and disadvantages. These are presented in Table 5-4. The key discriminator is whether a medium can be used for:

- Wide area network (WAN) communications between the dwelling and the energy supplier or other external entity.
- Internal "home area network" (HAN) communications within the dwelling, for example between an appliance and the energy management system.
- Both, normally with a concentrator that collects and relays data on behalf of a group of dwellings such as a street or block of flats.

Medium	Advantages	Disadvantages
Internet	Cheap and simple for WAN access if wireless broadband access available in household.	Poor security, not all households have wireless broadband, not suitable for HAN.
Mobile phone	Secure, easy to integrate into energy management system, but WAN only.	Contract required with service provider, some coverage limitations, not suitable for HAN.
Mains power line communications e.g. LonWorks	Fairly simple to integrate and install for HAN and WAN, mature technology.	Short range so needs local concentrators, relatively costly, few suppliers.
Mesh radio (Zigbee)	Designed for HAN and short range WAN, can be battery powered.	Needs a WAN concentrator, immature technology.

Table 5-4 Options for transmission medium

A variant of the mobile phone option based on text messaging was proposed by Boait (2002) and is now in use for some "smart" meters. A national power line communications network for metering and demand side management using LonWorks has been implemented in Italy (Canatelli, 2004). The Zigbee radio technology, specified in (Zigbee Alliance 2004), is becoming particularly attractive as products emerge from development, because it is also suitable for linking sensors to the energy management system. For example, external temperature measurements are preferably taken on the north side of a building to avoid peaks from insolation – a wireless sensor is much easier to install for this purpose than a cable run.

To allow millions of homes to be connected to a suitable network at low cost and exchange data with a range of external entities requires a national standardisation programme, to determine which transmission media will be employed and the application level protocols and data formats. The most promising standardisation initiative in the UK is that currently in progress by the Energy Retail Association (ERA) which has produced a detailed and comprehensive draft specification, the Smart Metering Operational Framework (ERA, 2007). Although focussed on metering, it covers all the forms of data exchange listed in Table 5-3, and also considers requirements from non-energy utilities such as water metering. Its development and adoption will depend on the view taken by other industry bodies and Ofgem. As introduction of smart metering is one of the headline commitments of the Energy White Paper (DTI, 2007) it seems likely that a national communications and data processing infrastructure will emerge that could provide a suitable platform for the innovations proposed in this thesis.

5.8 Overall Optimisation

Minimisation of exergy loss across a set of domestic energy sources and sinks is a straightforward linear programming problem amenable to the Simplex method invented by Dantzig and described in (Lapin, 1994). The Matlab implementation of this algorithm was used for the investigations described in 4.6. However, it is computationally expensive and implementing it in a real time control system is a substantial programming task, so for the prototype an alternative approach was sought. Also an energy management system capable of general application must be able to automatically define the objective function and inequality constraints. As the energy sources and sinks are in practice highly constrained it is possible to simplify the problem so that it can be solved, albeit approximately, by simple and reliable code.

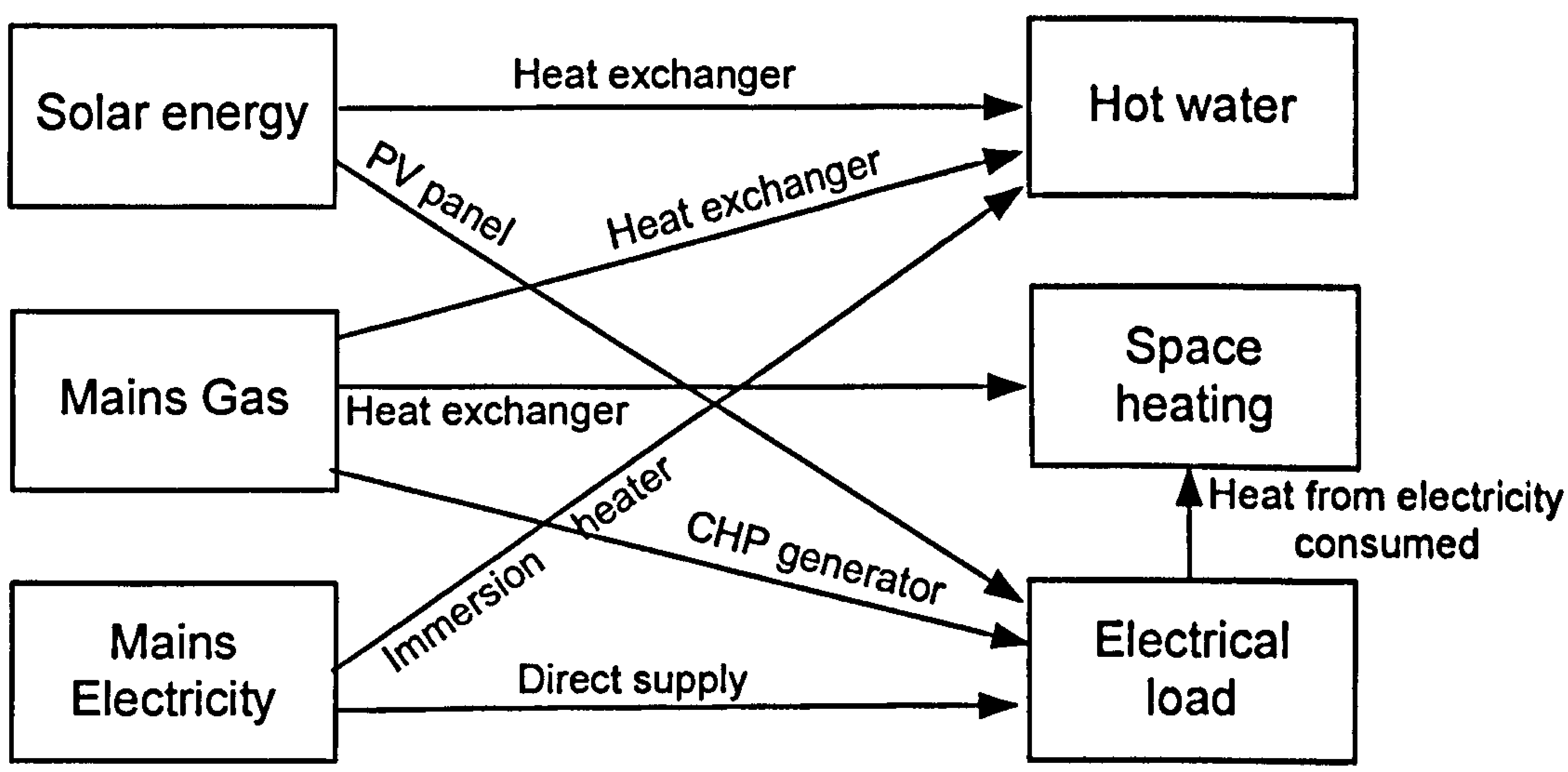

Figure 5-15 Energy sources, conversion devices, and sinks

The system must begin by establishing a mapping between the energy sources at its disposal, the energy conversion devices under management, and the energy sinks. Figure 5-15 performs this for the test bed. It also constructs a classification of their exergy content and requirement, and their controllability, as illustrated in Figures 5-16 and 5-17.

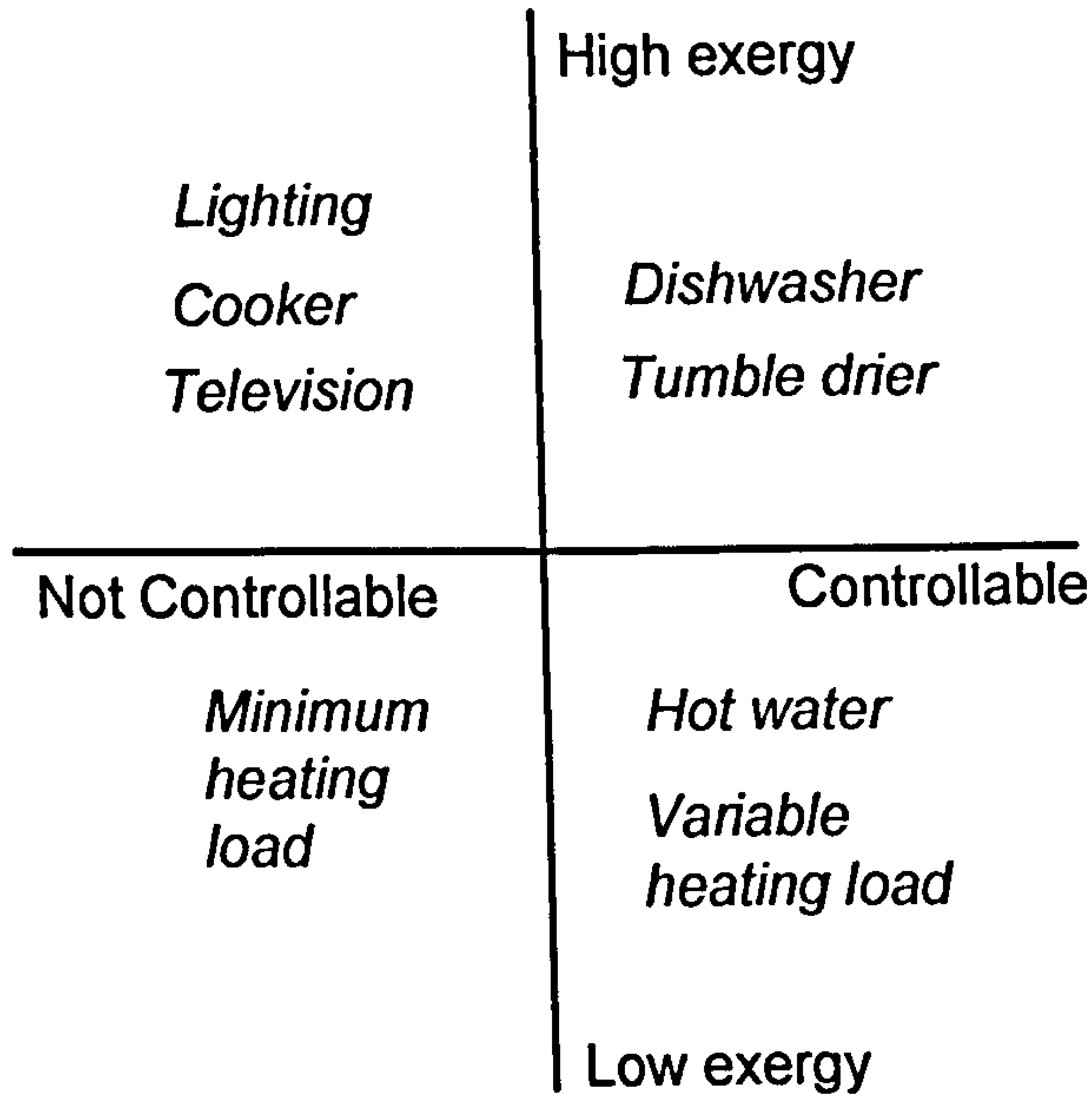

Figure 5-16 Controllability and exergy requirement of energy sinks

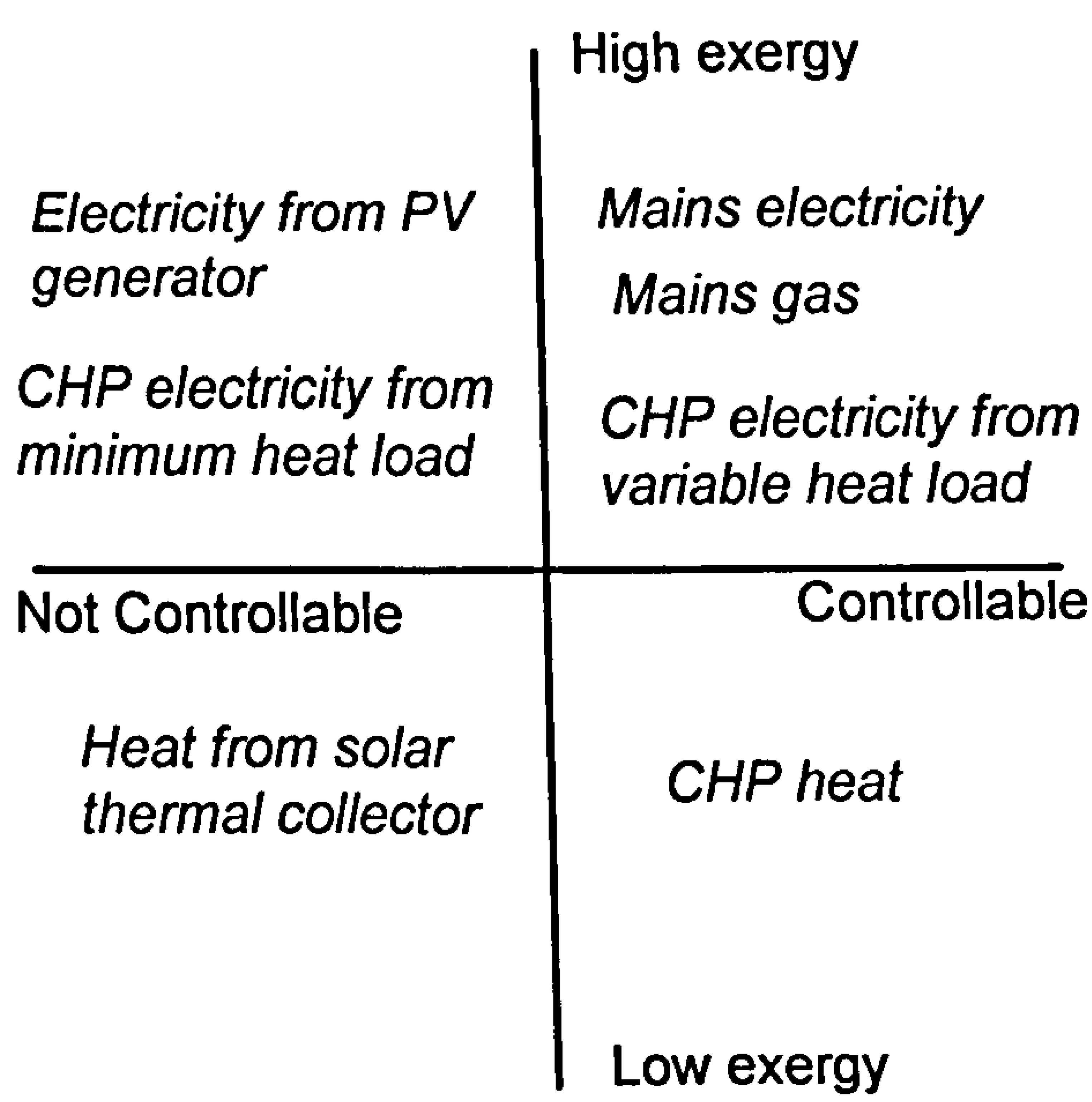

Figure 5-17 Controllability and exergy content of energy sources

With this taxonomy of the entities it is managing, the system can construct an operating schedule for the controllable devices using the process represented as a flow diagram in Figure 5-18. This is computed during the interval when the occupants are normally asleep, for the next 24 hours.

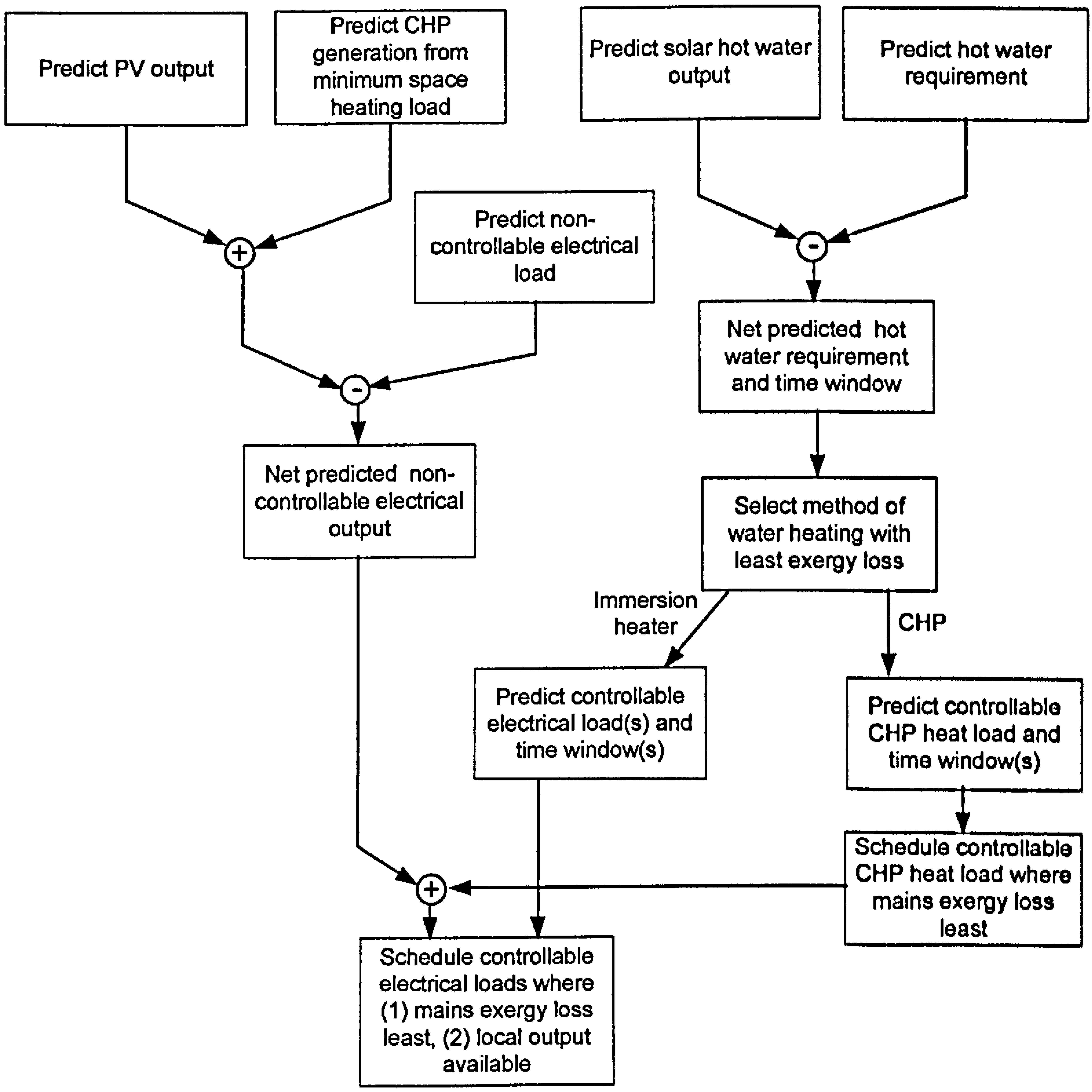

Figure 5-18 Simplified construction of an optimised schedule

The process in Figure 5-18 makes three decisions in the following sequence:

- If auxiliary heating is needed for the hot water, whether it should be provided by immersion heater or micro CHP.
- When to schedule the heat load to be met by the micro CHP that can be shifted in time (such as the hot water or an evening uplift in room temperature set point).
- When to schedule the electrical loads that can be shifted in time (such as the immersion heater or wet appliances).

The first decision is simple once the exergy loss performance of the relevant devices has been determined as described in 5.6. Micro CHP is likely to be chosen if there is sufficient minimum space heating load to avoid a start-up just for hot water, otherwise the immersion heater is used. The second is taken by treating the micro CHP electrical output arising from each controllable heat load as a block that can be slid in time anywhere within a window. The time with a maximum mains electricity exergy loss is chosen. The third decision places loads in a time window such that mains electricity exergy loss is minimised. Where mains electricity exergy loss is more or less constant within the window, the time which makes best use of locally generated electricity is chosen – this reflects the slight additional exergy loss from losses in the local distribution network if generator output is exported. The decisions in the latter two cases are computed by calculating the exergy loss for all available options at 5-minute time granularity and selecting the best.

5.9 Prototype Development and Results

The purpose of the prototype has been to show that some of the more innovative methods described in this chapter do work in practice. In particular, demonstration of the automatic detection of occupant behaviour patterns was a key objective, because it is hard to test through computer modelling since data are needed covering both sensor readings and corresponding minute-by-minute occupancy and activity levels. The main functions actually implemented were:

- Automatic setting of heating times
- Automatic detection of real-time behaviour and occupancy
- Automatic variation and adaptation of room temperature set point
- Measurement of hot water usage
- Optimised timing of hot water heating
- The user interface described in 5.4.

The prototype was coded in Microsoft Visual Basic 2005[13], using Visual Studio 2005 as the development environment with the hardware and operating software described in 3.6. The structure of the code is shown in Figure 5-19. For simplicity data is stored in the form of CSV[14] text files.

[13] An object-oriented update to the long established Visual Basic language.
[14] Comma Separated Variable

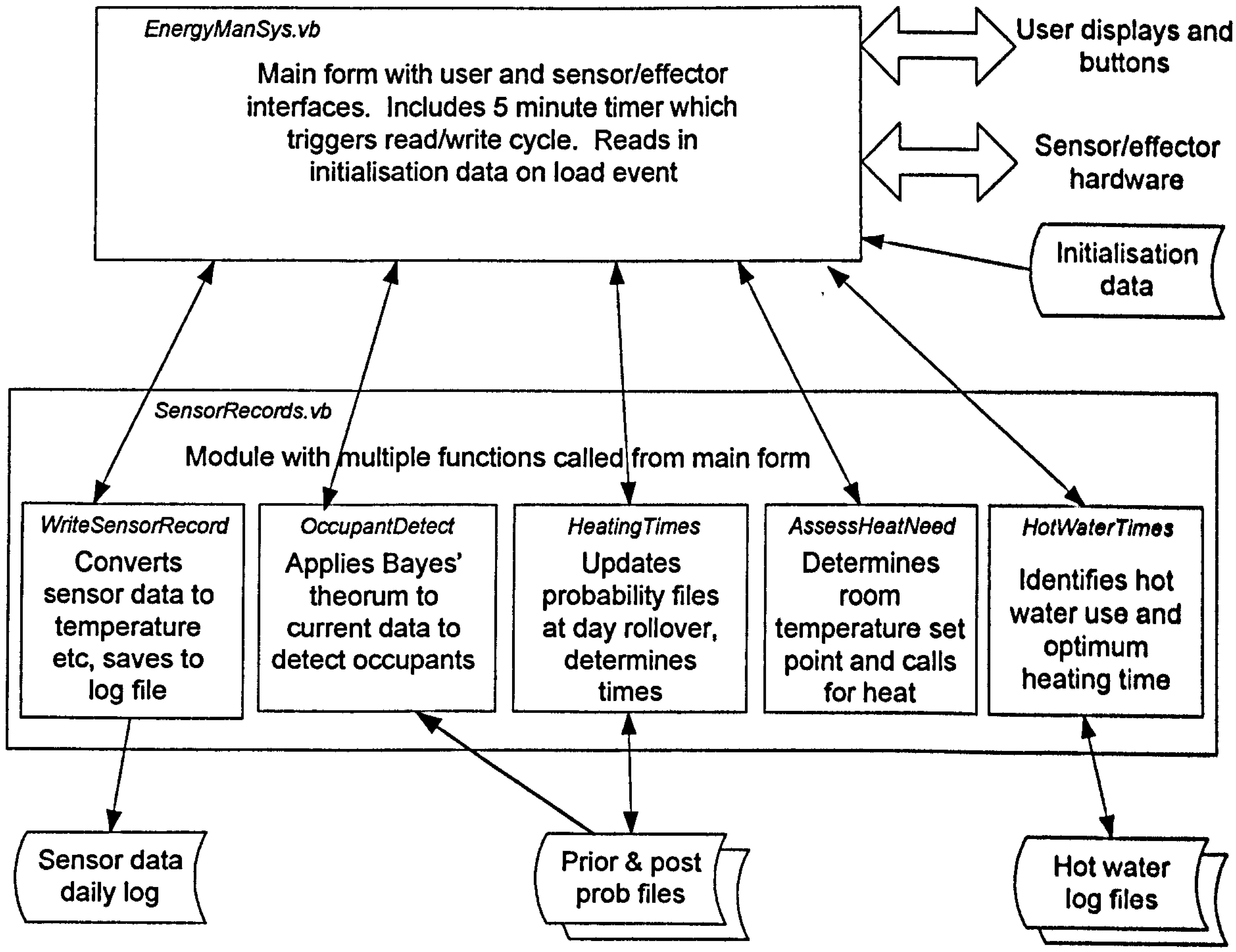

Figure 5-19 Program structure of prototype

This program was developed over several months during which it operated in "shadow" mode i.e. processing live sensor readings but with effector outputs monitored rather than controlling valves and heating. Once reliable and accurate behaviour was established, in early April 2008 it was cut over to full control of the heating system.

A detailed comparative analysis of heating performance was then performed for the two weeks before cutover, and the two weeks after. The results were more impressive than was expected in that gas consumption fell by 26% even though average external temperatures were very close for the "before" and "after" periods. However, examination of test bed records for the corresponding weeks in previous years showed that even where heating settings were held constant there was a fall in gas consumption of about 10%. This is caused by the commencement in early April of useful solar gain from the large area of south-east facing glazing at the rear of the house.
When this factor was taken out, and adjustments made for small differences in average external temperatures, electrical load, and electricity generated, the energy savings

attributable to the energy management system could be identified as shown in Table 5-5.

Source of energy saving	Reduction in heat output from micro CHP kWh/day	Reduction in gas consumed by micro CHP kWh/day	As % of daily "before" consumption
Lower average room temperature	10.7	12.8	9.4%
Improved operation of solar hot water heating	1.8	2.1	1.6%
Capture of heat from pump overrun	3.5	4.2	3.1%
Increased micro CHP efficiency		2.2	1.6%
Totals	15.9	21.4	15.7%

Table 5-5 Energy savings achieved by prototype management system

During the "before" period, the heating timer (as shown in Figure 2-8) was set for heating to be "on" between 06:45 and 23:00 every day, with a room temperature set point of 19.5 °C. Hot water heating was provided by a control arrangement known in the plumbing trade as a "W" plan. This requires that the hot water temperature is above the thermostat set point before space heating commences, so hot water is heated first if necessary when there is a demand for space heating. It also has the effect that the hot water cylinder is used as a sink for the residual heat from the micro CHP when space heating is ceased. This "W" plan is actually specified by Whispergen for their micro CHP because it is the most satisfactory configuration that can be achieved using simple control devices available from the average plumber's merchant.

Average room temperatures for the "before" and "after" periods are shown in Figure 5-20. The average room temperatures above the nominal set point during the "before" period arose from a combination of factors – the room thermostat had a wide and fluctuating hysteresis of about $\pm$ 1 °C, there were some days where solar gain was significant, and there was some use of an auxiliary heating source by the occupants. The lower temperatures during the "after" period arise from precise control of the room temperature set point, and a reduction in the time interval when a comfortable room temperature was required. This time interval was reduced from the fixed 16.75 hours per day "before" to an average of 11.7 hours per day "after", with a range from 5 hours to 15.5 hours reflecting accurately the variable occupancy during the two weeks "after".

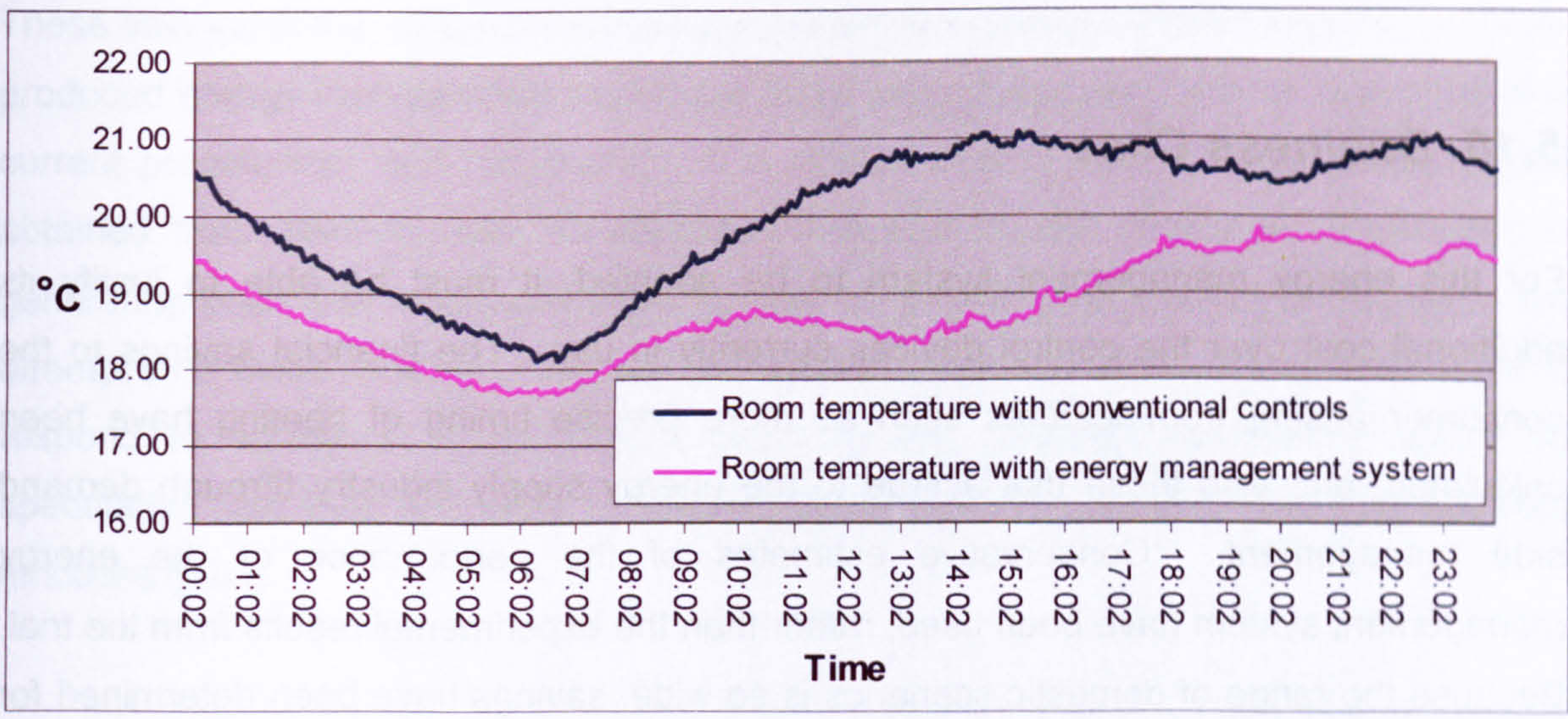

Figure 5-20 Average room temperatures before and after introduction of prototype

The improved output from the solar hot water heater was gained simply by optimised timing of auxiliary heating by the micro CHP. The management system also ensured residual heat from the micro CHP was delivered to space heating by operating a pump overrun function that kept water circulating in the radiator system after heat demand was dropped. These techniques combined with a lower average temperature in the radiator system led to a small but useful improvement in the micro CHP operating efficiency.

In making these savings the prototype has provided perfectly acceptable comfort at a time of year with variable weather conditions for a household with intermittent occupancy patterns. To achieve this certain parameters were found to be critical:

- The likelihood values associated with sensor readings i.e. the probability that a given reading is obtained when occupants are active.

- The averaging period used to convert daily post probabilities into prior probabilities. A short period responds faster to changes in behaviour but is correspondingly liable to be further away from the mean behaviour pattern.

- The persistence associated with detection of occupancy. Since some of the events used to detect occupancy are short lived, such as use of hot water or an electric kettle, the system must assume that occupancy lasts beyond the event and provide heating accordingly. A short persistence time ensures that periods when the dwelling is unoccupied are recognised, but increases the risk that comfort expectations will not be satisfied.

Investigation of the sensitivity of these parameters in different domestic situations is clearly an important topic for the next stage of development.

5.10 Business Case

For this energy management system to be adopted, it must be able to justify its additional cost over the control devices currently in use. The financial savings to the consumer arising from features such as more precise timing of heating have been calculated, and also those that accrue to the energy supply industry through demand side management. Conservative estimates of the performance of the energy management system have been used, rather than the experimental results from the trial. Because the range of domestic scenarios is so wide, savings have been determined for a single representative household but considering several possible "equipment fits" of energy conversion devices. The top part of Table 5-6 below summarises the results obtained by showing the savings generated by each of the functions described in this chapter, for a household with an annual space heating requirement of 12,000 kWh, electricity consumption for appliances and lighting of 4,000 kWh, and needing 3,000 kWh of hot water of which 1,000kWh are supplied from a solar hot water heater. The four energy equipment options (labelled A-D) are:

A. Gas boiler (combi or conventional) providing space and auxiliary hot water heating.

B. Micro CHP providing space and auxiliary hot water heating, and heat led electrical output of 1kW.

C. Electrical storage radiators for space heating and an immersion heater for auxiliary hot water.

D. Non-manageable space heating (e.g. wood burning stove) with an immersion heater for auxiliary hot water.

The auxiliary hot water source is used to meet demand in excess of that provided by the solar hot water panel. The space heating load was modelled using degree day data published by the Carbon Trust (2008) for a dwelling located in the Severn Vale, and assuming a building specific heat load of 280 W/°C and thermal capacity of 10 kWh/ °C. Tariffs assumed are 5p per kWh for overnight electricity under an Economy 7 contract, 10p per kWh for electricity otherwise, 3p for gas. The lower part of the table shows the baseline energy costs allowing the savings to be expressed as a percentage.

These savings in the range £29 to £76 per annum are clearly sufficient to justify a mass-produced energy management system as proposed costing say £120 i.e. twice that of a current programmer and thermostat. It is notable that by far the largest savings are obtained from demand side management, because capital investment is avoided in generating plant that would otherwise be needed to meet the early evening peak. No attempt has been made to estimate the savings from managing storage radiators to respond to variations in wind generation, as the assumptions needed would be speculative, but they are likely to exceed those from the demand side management functions given.

Function	£ saved per annum				Additional assumptions
	A	B	C	D	
Tighter timing of space heating	7.30	7.30	10.34		85% efficiency assumed for gas boiler and micro CHP
Improved local consumption of micro CHP electricity output from tighter timing		3.00			£0.04 per kWh spread between import and export
Adaptive room temperature set points	14.82	14.82	21.00		85% efficiency assumed for gas boiler and micro CHP
Improved local consumption of micro CHP electricity output from adaptive room temperature set point		15.00			£0.04 per kWh spread between import and export
Immersion heater demand side management				50.88	£1000 per kW plant capital cost, £30 per kW maintenance.
Micro CHP demand side management		29.58			£1000 per kW plant capital cost, £30 per kW maintenance.
Improved timing of auxiliary water heating	2.93	2.93	4.15	8.30	85% efficiency assumed for gas boiler and micro CHP
Summer switch-off of gas boiler	3.60				25W idle electricity consumption
Summer switch-off of micro CHP		3.25			22.5W idle electricity consumption (as measured for Whispergen)
Total saving £ per annum	28.65	75.88	35.49	59.18	
Baseline energy costs £ per annum	£896	£784	£1,102	£600	Option D excludes space heating
Saving as percentage of baseline	3.2%	9.7%	3.2%	9.9%	

Table 5-6 Financial savings from energy management system

6 CONCLUSIONS

6.1 Demonstration of the Hypothesis

The arguments set out in Chapters 2 and 4 to support the hypothesis can be reduced to two key points:

- All the other plants and animals on the planet manage their energy flows by seeking and conserving exergy, so it's probably a good strategy for humans as well.
- You can't trust a market price as a signal to control an engineering apparatus because markets are a social construct driven in part by human emotions such as fear and greed.

A sceptic might well respond: "Wait a minute, some of the animals, and maybe even plants in a kind of way, in that ecosystem you hold up as a model experience fear and greed as well. What's the difference?" The answer is that in the ecosystem Darwinian selection pressures and the limitation to a single local energy source, the solar gradient, together constrain the populations of plants and animals in accordance with the physics of energy, as shown by Ulanowicz (2006), Schneider and Sagan (2005) and others. In the case of the market, pricing is dominated by the availability of fossil fuels that are unevenly distributed around the world, and while Darwinian selection in the form of open warfare for these resources would result in rapid convergence with the ecosystem model, in practice 21st century politics rightly eschews such brutality. So natural gas, for example, can be expected to continue to oscillate in price depending on the weather, the post-communist politics of Eastern Europe, the reliability of liquefied petroleum gas distribution systems, and the emotional mood of speculators in this commodity.

An adherent to rational market theory would argue that in the long run prices are rational and while short term variations occur, there are also cyclic population fluctuations observable in many ecosystems. There is a ring of truth to this argument, which is supported by the practical consistency between cost and exergy loss signals shown in Chapter 4, although no ecosystem exhibits anything like the hour-to-hour variability shown for electricity wholesale prices in Figure 4-8. If the economist's argument is accepted in its long term aspect, it reduces the distinction between cost and exergy loss signals to one very recognisable to an electronic engineer: it is a matter of signal-to-noise ratio. This thesis argues that exergy loss has a much better signal to noise ratio because it is free from short term market noise. The only noise that is present arises from the difficulty of calculating exergy loss accurately in all circumstances. This noise is predictable i.e. the uncertainties can be estimated, and the signal can be processed taking them into account. This is not true of market variations.

A good signal to noise ratio in the controlling metric of energy systems is vital for the other central implication of the thesis, growth in complexity. An analogy is the rollout of digital broadcast television. Most people on buying a decoder box are forced to get a new aerial on the roof as well in order to get it to work properly. In other words they have to improve their signal to noise ratio. In return they get many more channels to watch – the richness and diversity of content available to them is greatly extended[15]. This is a consequence of the Shannon-Hartley theorem that expresses the dependency of channel capacity on signal to noise ratio[16]. Given the arguments from basic physics in Chapter 2 that the route to greater energy efficiency is through complexity and diversity, it can be seen that the clear signal offered by exergy loss minimisation is an essential prerequisite.

If this argument is accepted, then the "so what" question arises – how would national energy policy be affected? Probably the most important outcome of a systematic policy to minimise exergy loss (in addition to proliferation of the devices proposed by this thesis) would be far greater use of district heating from CHP plants. Such plants, operating with an adjustable ratio of heat to electrical energy, would be able to act as a flexible resource able to respond to periods of low output from renewable sources, and thereby, in combination with the demand side management measures described in Chapter 4, resolve the intermittency issue as a constraint on the adoption of renewables. As the capacity of low carbon electricity generation builds, it will be able to supply the plug-in hybrid vehicles and heat pumps which will also be incentivised by this policy.

6.2 Knowledge Gained and Progress towards Aims

In Chapter 3 the measured performance of a micro CHP unit was reported, and these results were extrapolated by modelling a range of domestic building and occupation scenarios. The key results are summarised in Table 6-1 below and compared with those published by other authors based solely on modelling. The greater electrical export energy (44% of generator output) indicated by the practical measurement is of

[15] This assertion should be considered on the basis of information theory rather than the artistic merit of channel content.
[16] The upper bound C on the error free data rate that can be sent with signal power S through a channel with noise power N and bandwidth B is given by $C = B\log_2(1+S/N)$.

considerable importance to policymakers and regulators because it confirms and strengthens the need for fair export contracts to be offered to consumers if this low carbon technology is to be adopted. Using the electricity demand modelling tool developed by Stokes (2005) in combination with the micro CHP model developed in this study and calibrated against the experimental equipment, it has also been shown that accurate predictions of export levels can be made with a suitably fine-grained model of demand, and that export levels up to 60% can be expected for homes with below average occupancy.

The experimental and modelling work around micro CHP also investigated how both cost and exergy loss could be reduced by aligning generator output with electrical load through improved precision in operating time settings and manipulation of the room temperature set point.

Parameter	**Measured result**	**Harrison & Redford (2001)**	**Peacock & Newborough (2005)**
Total generator output over a year	2940 kWh	3000 kWh	2610 kWh
Proportion of generated electricity exported	44%	15%	40%

Table 6-1 Comparison of actual micro CHP performance with predictions

Having established a good basis of experimental data on the performance of microgenerators, and models allowing extrapolation of results to a more general scale, this study has sought solutions to the engineering requirements inherent in the thesis as identified in 2.2 and detailed in Chapter 4. Of these the most challenging is the reconciliation of the limited ability of users to manage their own energy conversion devices with the need for increased complexity and diversity that is implied by the ecosystem model of optimum energy use. The proposed way forward is an energy management system that can acquire information and make day-to-day decisions based on a management policy derived from an initial lifestyle setting, while allowing consumers to signal any variations they need to the management policy. The conceived system can also accommodate new energy conversion devices on a plug-and-play basis, and meter or monitor their performance as required. The innovations that have been made to achieve this, and corresponding patent applications taken out, are summarised in Table 6-2 with in indication of the current status of the applications.

Topic	Patent application number	Application date	Current status
Automatic setting of heating times using Bayesian inferencing from electrical load and lifestyle setting	GB 2432016	4 Nov 2005	Granted 6 November 2007
Automatic recognition of renewable energy sources by time and frequency domain pattern matching	GB 0702392.2	8 Feb 2007	Search completed, no objections. This application was considered plural resulting in the other applications based on this technique.
Metering of renewable and CHP electricity generators by time and frequency domain pattern matching	GB 0806212.7	1 April 2008	Search completed under 0702392.2, no objections.
Prediction of the output energy of renewable and CHP devices.	GB 0806214.3	1 April 2008	Search completed under 0702392.2, no objections.
Energy management system using the all the proposed data capture and optimisation methods	GB 0708448.6	2 May 2007	Search objections raised, response provided.

Table 6-2 Patent applications from this study

An assessment may be made of the progress achieved by this body of work against the three aims of the project set out in Chapter 1. The first aim was:

> *"to devise an optimum technique by which large numbers of domestic scale generators can be economically controlled, metered, and monitored"*

Generator control has been addressed through the proposed exergy loss broadcast (4.6.2), metering through generator pattern recognition (5.6), and monitoring through energy conversion device characterisation (also 5.6). These techniques are capable of being deployed at a national scale - the exergy loss broadcast uses the existing radio teleswitch infrastructure, while the metering and monitoring methods are ideal as software applications that would add value to the national smart metering rollout that is beginning to get under way as discussed in 5.7.

The second aim intended:

"to demonstrate a method for collective optimisation of domestic energy conversion and consuming devices"

Exergy loss minimisation is the proposed method for collective optimisation that has been evaluated by comparison with minimisation of carbon emissions (4.4) and cost (4.5), then tested through modelling investigations (4.6) and the prototype energy management system (5.8-5.9).

The final aim was:

"to improve the information on, and control of, energy use available to the consumer"

The counter-intuitive finding from the literature review was that "less is more" as far as consumer information and control is concerned, so the human interface proposed (5.4 and Figure 5-5) provides the minimum information necessary to assure the user that their needs are being met and to encourage them to economise in electricity use. It limits and simplifies the control offered to the user while maintaining the psychological comfort of adaptive opportunity.

6.3 Further Work

The programme of practical and experimental work that has been undertaken in this study has been limited in several aspects:

- Data collection and testing has been confined to a single house and occupancy pattern.
- The application of the control methods to energy conversion devices not represented in the test bed, such as heat pumps, has not been investigated in detail.
- Some of the algorithms implemented in the prototype are simple and capable of improvement. For example, the determination of room temperature set point from a wide range of factors would probably benefit from application of neural network techniques, and optimisation from use of the Simplex method.

To become a viable consumer product the proposed energy management system requires a sustained programme of trials and engineering development that will address these limitations. This is now in progress. If the ecosystem model of energy capture and management proposed in this thesis has merit at the domestic scale, the research question to carry forward must be "can an ecosystem model of energy capture and use operate at district, regional, or national scales?". The nesting of localised ecosystems within larger systems is a readily observed feature of the natural world so this seems a reasonable proposal, and a consistent objective function at all scales would enhance operation at each scale. However, apart from the engineering issues which would be the natural focus of a sequel to this work, the obvious challenge is the reconciliation of this model with practical economics. Fortunately the reconciliation of free market economics with the imperatives of sustainability and climate change is a very active area of research and policy making – for example Ekins *et al.* (2003) propose a framework for reshaping economic incentives. Porritt (2005) recognises the particular merit of making the technosphere behave like the biosphere:

> "Biomimicry provides one of the most visionary approaches to meeting the overarching challenge of aligning humankind's model of progress and growth with nature's systems and processes..........the wholesale shift from hydrocarbons to solar/renewable technologies is perhaps the most likely place where this may happen"

So the vision from this thesis is that the rich pool of technology developed for the mobile phone and the ipod can be exploited to provide the nervous system and intelligence within an artificial ecosystem of man-made devices performing energy capture, distribution, storage, and use. A small step has been made in this direction, but there is a long way to go.

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